Racket and FP

Break up into pairs: find someone that has Dr. Racket

(Yes, you have to participate..)

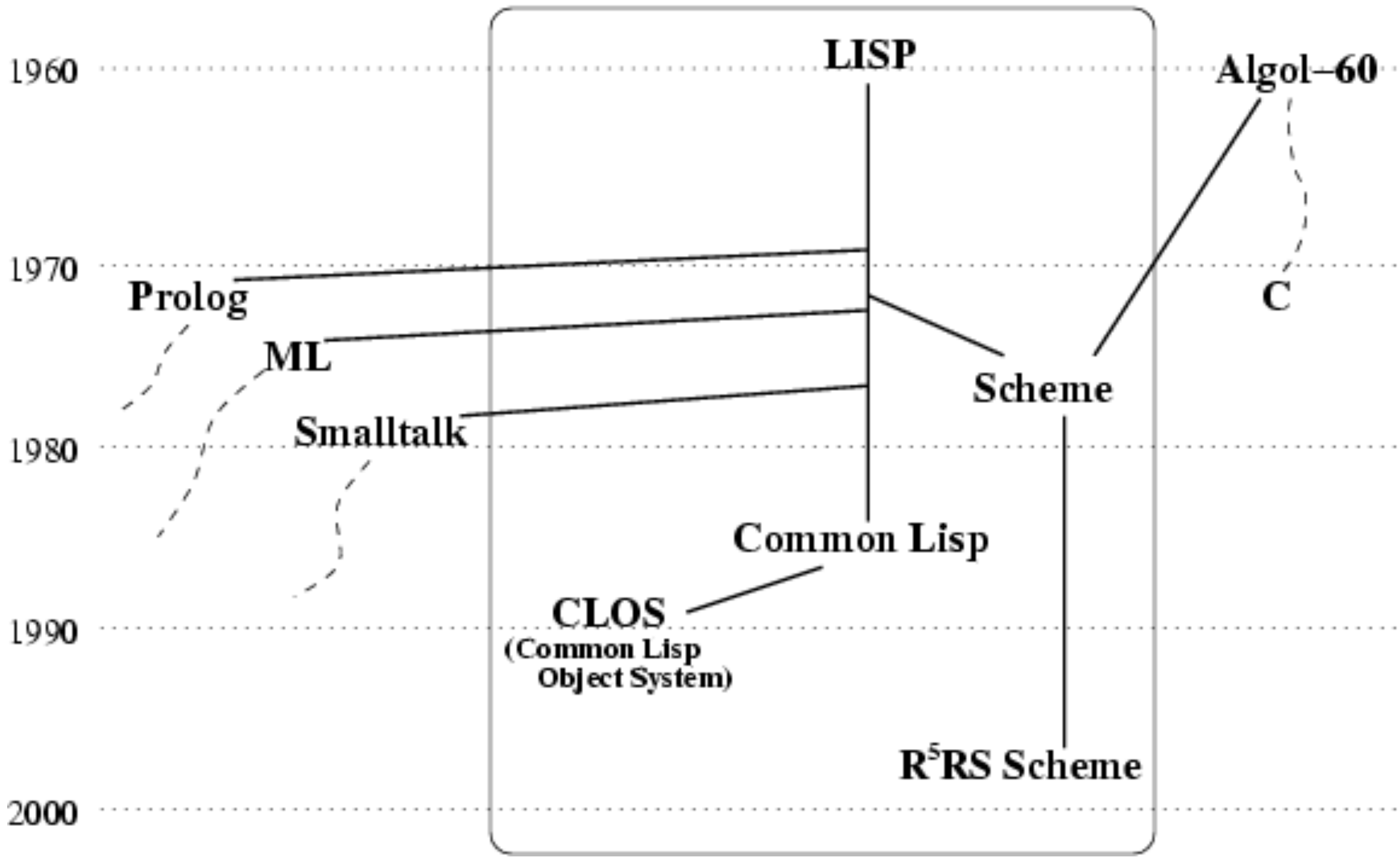
λ

Kris talks about failure

Racket

- Dynamically typed: variables are untyped, values typed
- Functional: Racket emphasizes functional style
  - Immutability—Requires automatic memory management
- Imperative: Racket allows values to be strongly-updated, and is thus "impure" as functional languages go
  - Often discouraged
- Language-Oriented: Racket is really a language **toolkit**

A brief tour of history…



1960
1970
1980
1990
2000
LISP
Algol–60
Prolog
ML
Smalltalk
Scheme
C
Common Lisp
CLOS
(Common Lisp
Object System)
R5RS Scheme

We wanted a language that allowed **symbolic manipulation**

List of either **atoms** or **S-expressions**

(this (is an) (s) expression)

List of either **atoms** or **S-expressions**

(this (is an) (s) expression)

List of either **atoms** or **S-expressions**

(this (is an) (s) expression)

atom

List of either **atoms** or **S-expressions**

(this (is an) (s) expression)

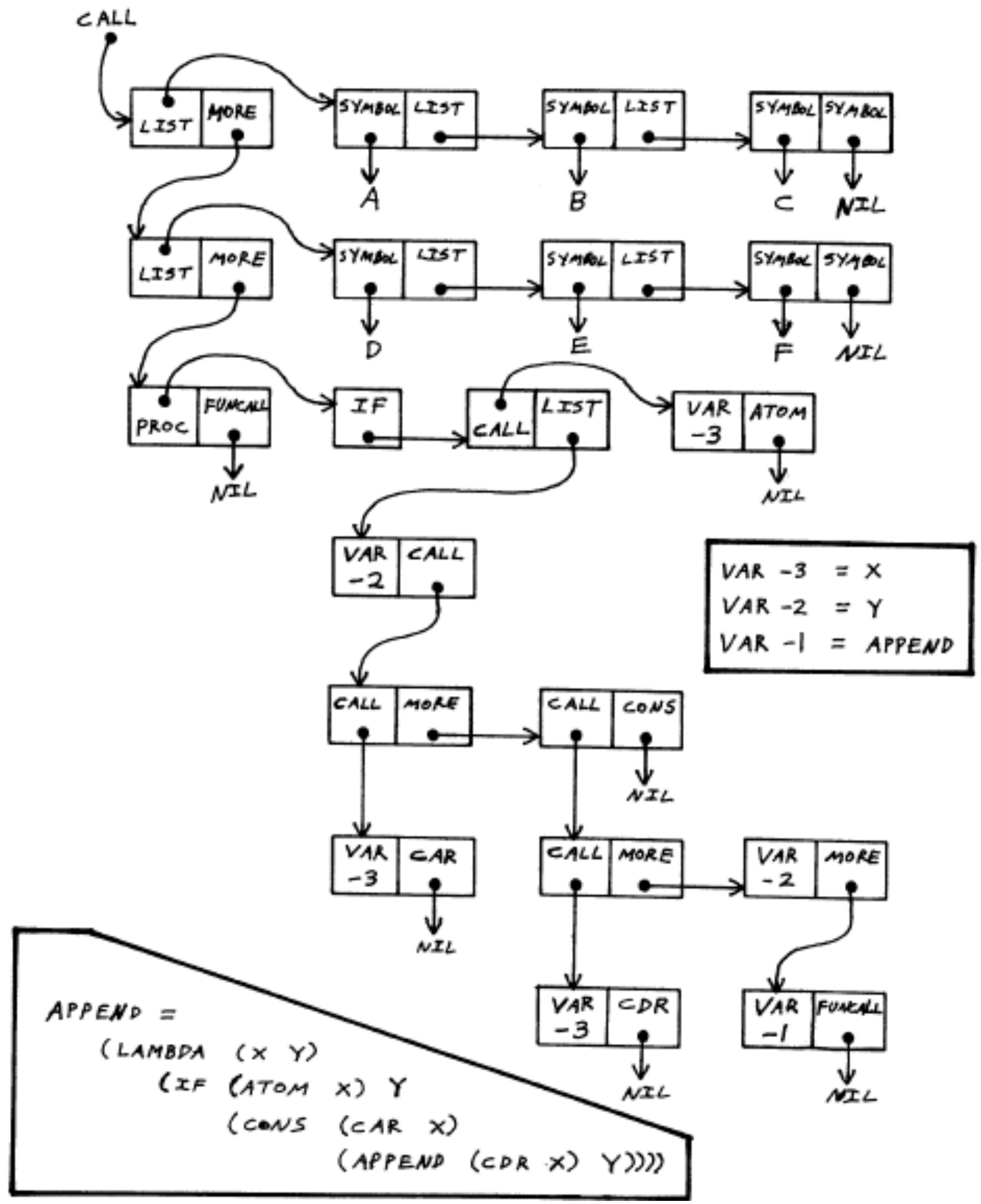
S-expression

List of either **atoms** or **S-expressions**

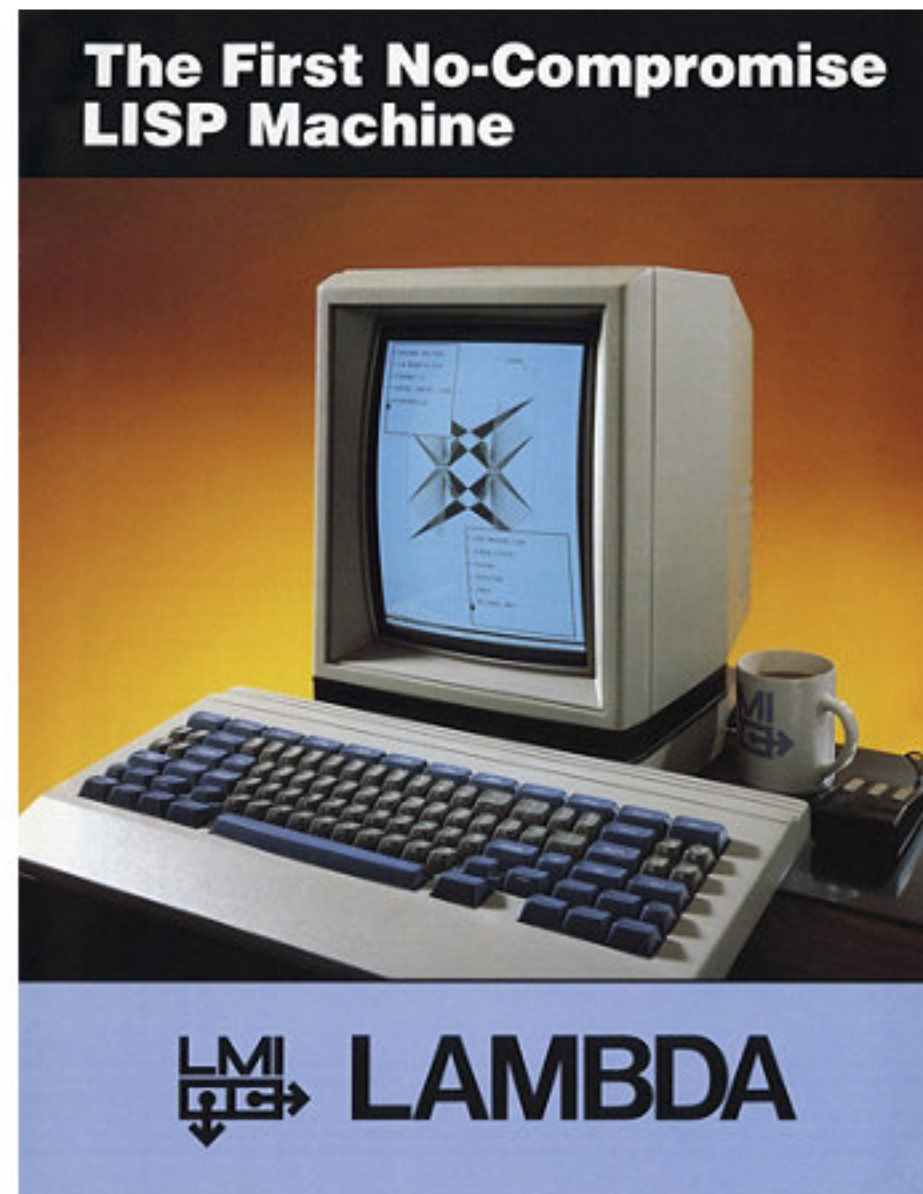
(this (is an) (s) expression)

also an S-expression

SIMPLE Expression for (APPEND '(A B C) '(D E F))




LAMBDA


The First No-Compromise
LISP Machine
LMI
LAMBDA


QUOTE
OVER STRIKE
CLEAR INPUT
CLEAR SCREEN
HOLD OUTPUT
STOP OUTPUT

So how do we write programs in this?

Calls `function` with arguments $\texttt{arg}_0$, $\texttt{arg}_1$, etc…

```
(function arg₀ arg₁ …)
```

No infix operators! Everything is like this..

Two examples with + and -

Quiz problems: + and -

Calculate (1 + (2 - 3)) - 4

Introduce `if`, `and`, `or`

```
(if #t 1 2)

(if (equal? 2 3) 1 2)

(if (< 3 4) 1 2)

(if (and (or #t) #t) 1 2)
```

Notice: there is no “return” value

In functional programming, **every single expression** implicitly returns its resulting value

```
(and #t #f)

(or #t …)
```

Always true, even if … doesn't terminate!

```
(define (factorial x)
    (if (equal? x 0)
        1
        (* (factorial (- x 1)) x)))
```

```
(define (factorial x)
    (if (equal? x 0)
        1
        (* (factorial (- x 1)) x)))
```

- Everything in parenthesis
- Prefix notation
- No variable assignment
- Recursion instead of loops
- No types
- No return

Quiz

- Compute the factorial of 5
- Compute the factorial of 20
- Compute the factorial of 20000

Quiz

- Define the fibonacci function:
  - Use `if`, `equal?`, `-`
- `fib(0) = 1`
- `fib(1) = 1`
- `fib(n) = fib(n-1) + fib(n-2)`

Introduce **cond**

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```
(cond
  ([= x 1] 1)
  ([= x 2] 2)
  (else 3))
```

Introduce **cond**

```
(cond
   ([= x 1] 1)
   ([= x 2] 2)
   (else 3))
```

Any number of conditional “clauses”

Introduce **cond**

```
(cond
  ([= x 1] 1)
  ([= x 2] 2)
  (else 3))
```

Potentially an “else” clause

Introduce **cond**

```
(cond
   ([= x 1] 1)
   ([= x 2] 2)
   (else 3))
```

cond checks each clause and executes the body of the first one that matches

If you get stuck, use the debugger…!

Racket is *dynamically typed*

```
> (length 2)
length: contract violation
  expected: list?
  given: 2
> 
```

```
(define (fib-again x)
    (cond
      [(< x 0) (raise ‘lessthanzero)]
      [(eq? 0 x) 1]
      [(eq? 1 x) 1]
      [else 0]))
```

Define max

- `cond`
- `<`
- `>`
- `equal?`

Most Racket data is based on **lists**

```
‘(1 2 3)
```

Most Racket data is based on **lists**

```
‘(1 2 3)

(first ‘(1 2 3)) -> 1

(rest ‘(1 2 3)) -> ‘(2 3)

(rest ‘(3)) -> ‘()
```

Can use **empty?** to check

```
(empty? ‘())

(empty? ‘(1 2))
```

Pronounced “empty-huh?”

Define max-of-list

- `empty?`
- `first`
- `rest`
- `length?`

Can create local variables with **let**

```
(let ([x 2]
      [y 3])
  (+ x y))
```

“Let x be 2 and y be 3 inside the expression…”

Quiz

Define `(distance x1 y1 x2 y2)`

Use `sqrt`

Use **let** at least once

You can create **anonymous** functions with lambda

```
(lambda (x) (- x))

(lambda (str) (string-ref str 0))

((lambda (x) (* x x) 3)

(define f (lambda (x) (* 2 x)))   (f 3)
```

```
(let ([x 1])
  (+ x 1))
```

Rewrite this in terms of lambda!

Transform..

```
(let ([x 1])
  (+ x 1))
```

```
((lambda (x)
   (+ x 1)) 1)
```

Let is λ

```
(let* ([x 1]
       [y (+ x 1)])
 (list y x))
```

Lots of other things are λ too…

```
(define (f x) x)
```

↓ shorthand for…

```
(define f (lambda (x) x))
```

```
(define (f x) x)

(define f (lambda (x) x))

(define (f x y) x)

(define f (lambda (x y) x))

...
```

Here's what most confused me…

```
> (lambda x x)
#<procedure>
> (lambda (x) x)
#<procedure>
> (lambda (x) x) 1
#<procedure>
1
> ((lambda (x) x) 1)
1
> ((lambda x x) 1)
'(1)
> |
```

Define hyphenate

```
> (hyphenate '("Kristopher" "Kyle" "Micinski"))
"Kristopher-Kyle-Micinski"
> |
```

(Use `string-append`)

Using higher order functions…

If you give me a function, I can use it

```
(define twice
  (lambda (f)
    (lambda (x)
      (f (f x)))))
```

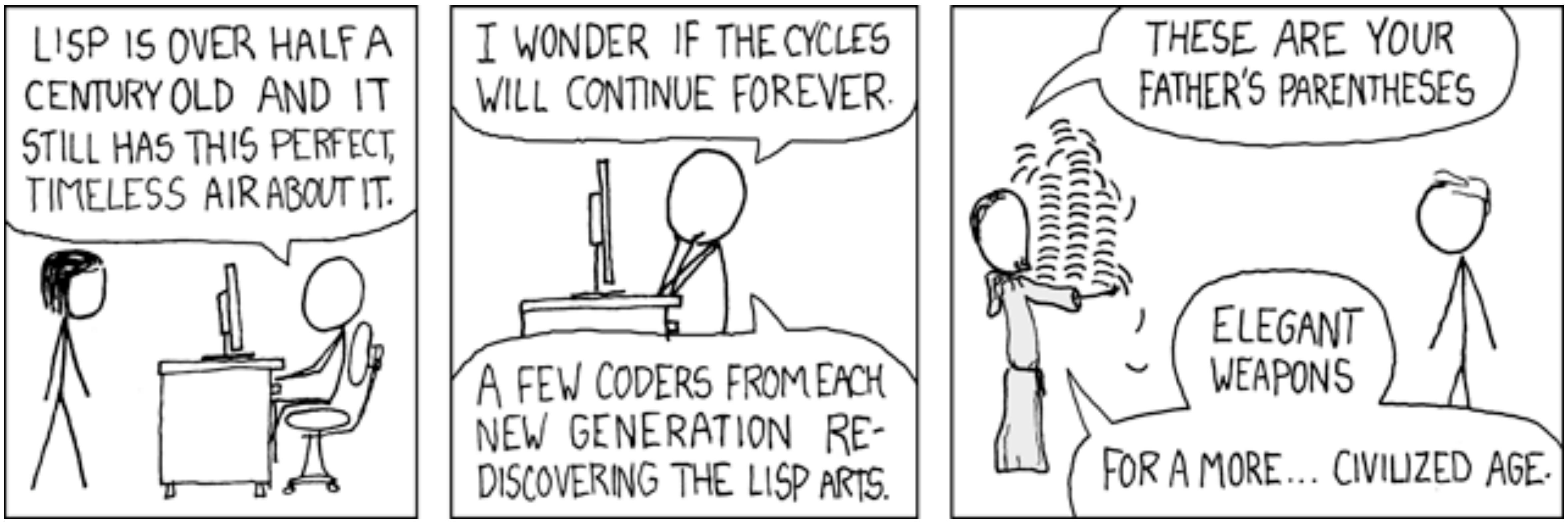
Challenge: figure out how I would use twice to add 2 to 2

Use Racket's add1 function

```
(add1 (add1 2))
```

All the forms we covered today:
Define, let, lambda, cond, if

Data Structures via Lists


LISP IS OVER HALF A CENTURY OLD AND IT STILL HAS THIS PERFECT, TIMELESS AIR ABOUT IT.
I WONDER IF THE CYCLES WILL CONTINUE FOREVER.
A FEW CODERS FROM EACH NEW GENERATION RE-DISCOVERING THE LISP ARTS.
THESE ARE YOUR FATHER'S PARENTHESES
ELEGANT WEAPONS
FOR A MORE... CIVILIZED AGE.

In today's class, we're going to build all data from three things…

The first is **atoms**

These are the *primitive things* in the language ‘symbol

1

These are like "`int`" and "`char`" in C++

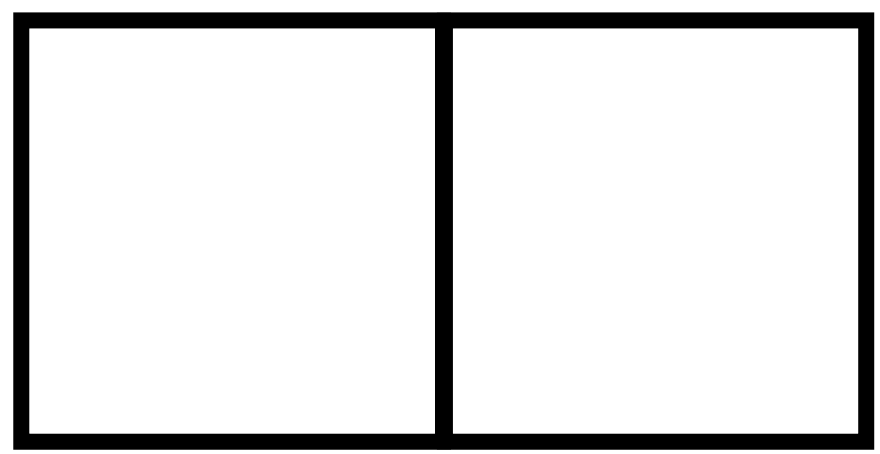
The second is the **empty** list

‘O

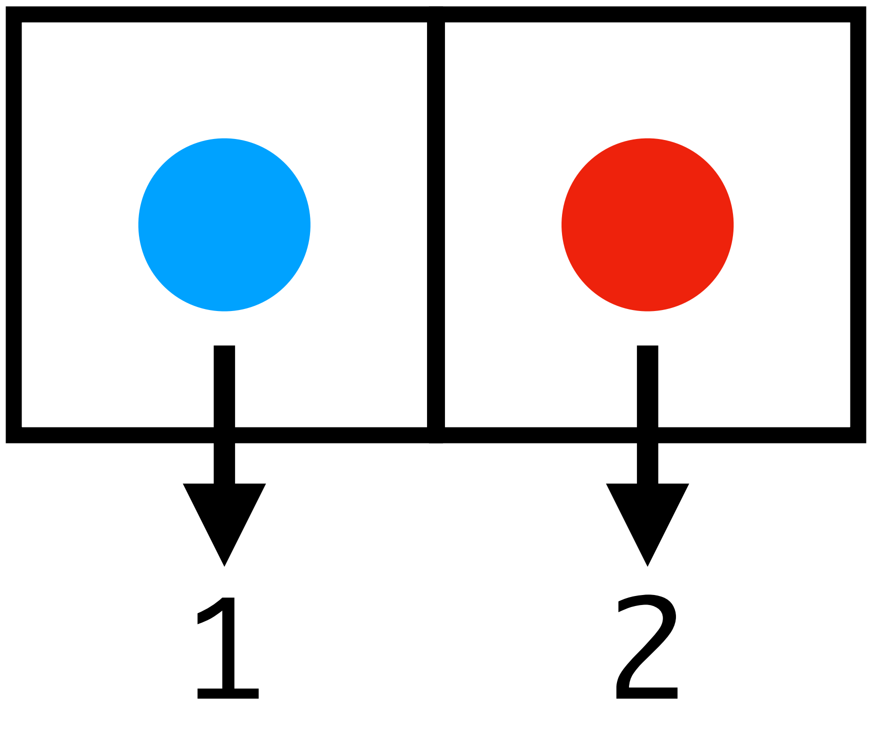
The last is **cons**

Cons is a function that takes two values and makes a pair

That pair is represented as a **cons cell**

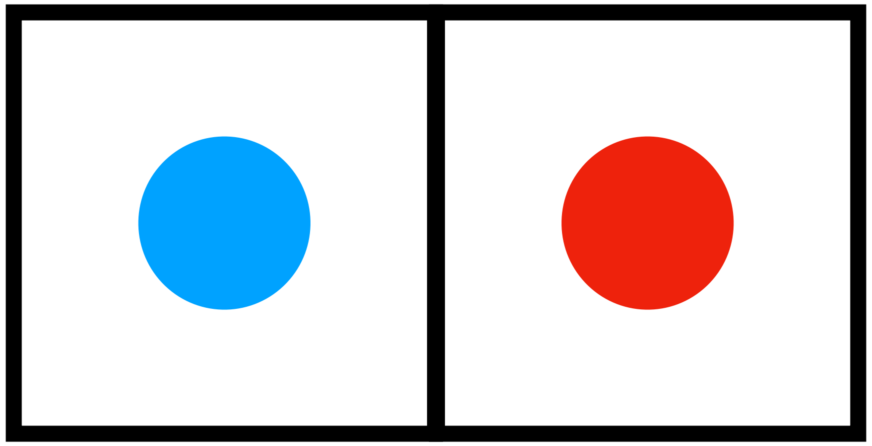


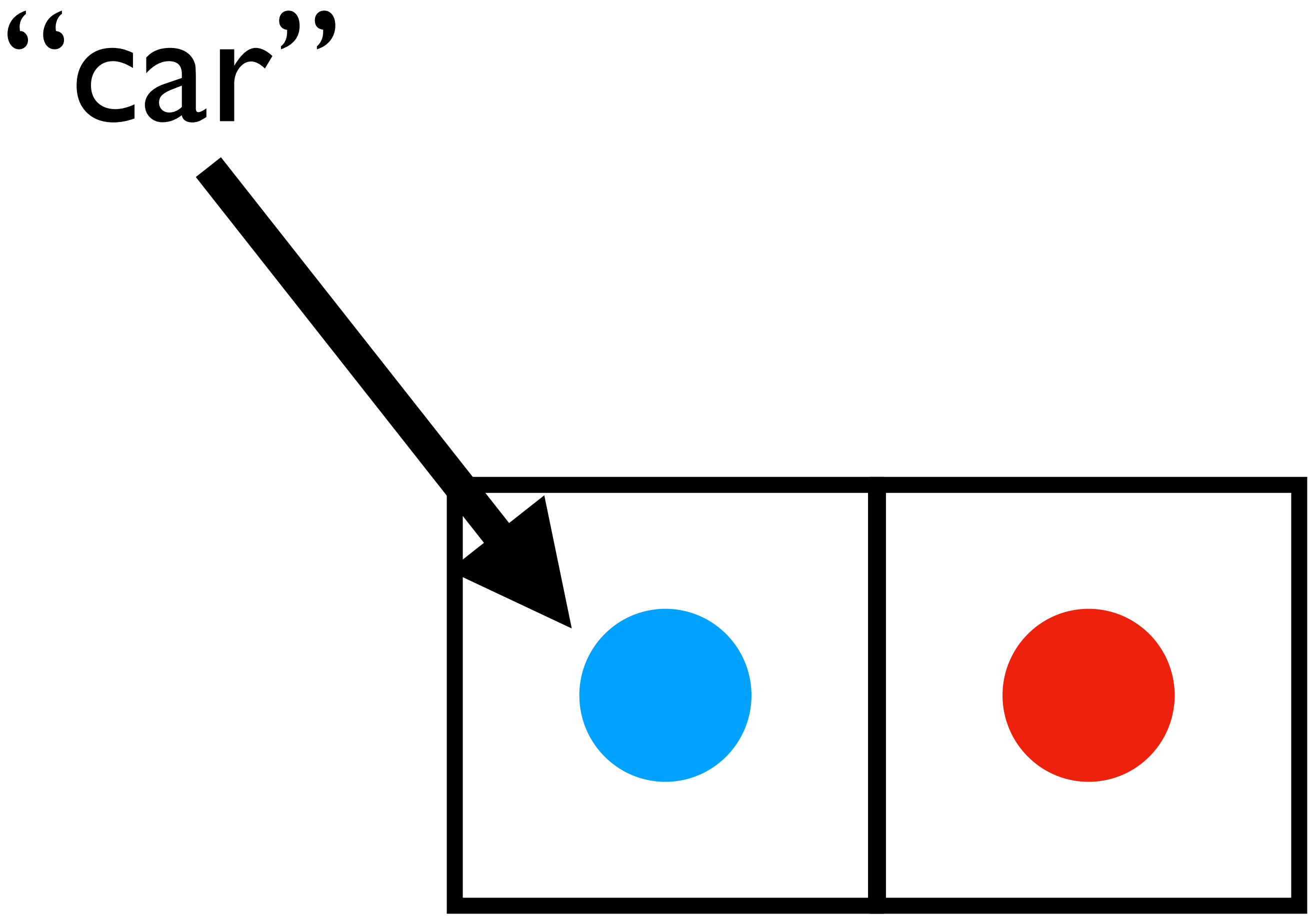
(cons 1 2)

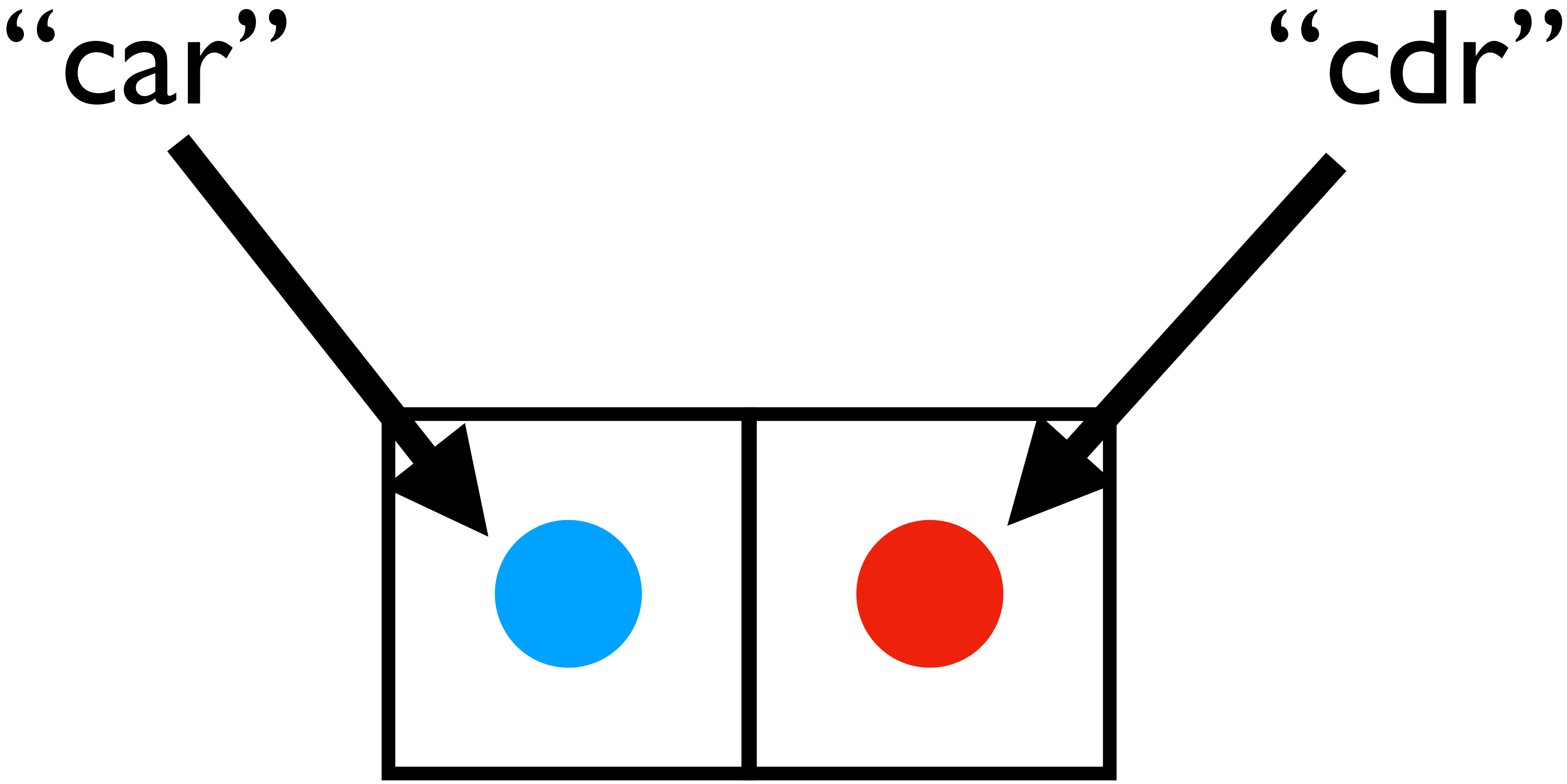


cons is the the natural **cons**tructor of the language

I use two strange words to refer to the elements of this cons cell




“car”


“car”
“cdr”

Because car and cdr break apart what I build with cons, I call them my **destructors**

And that’s all

And that's all

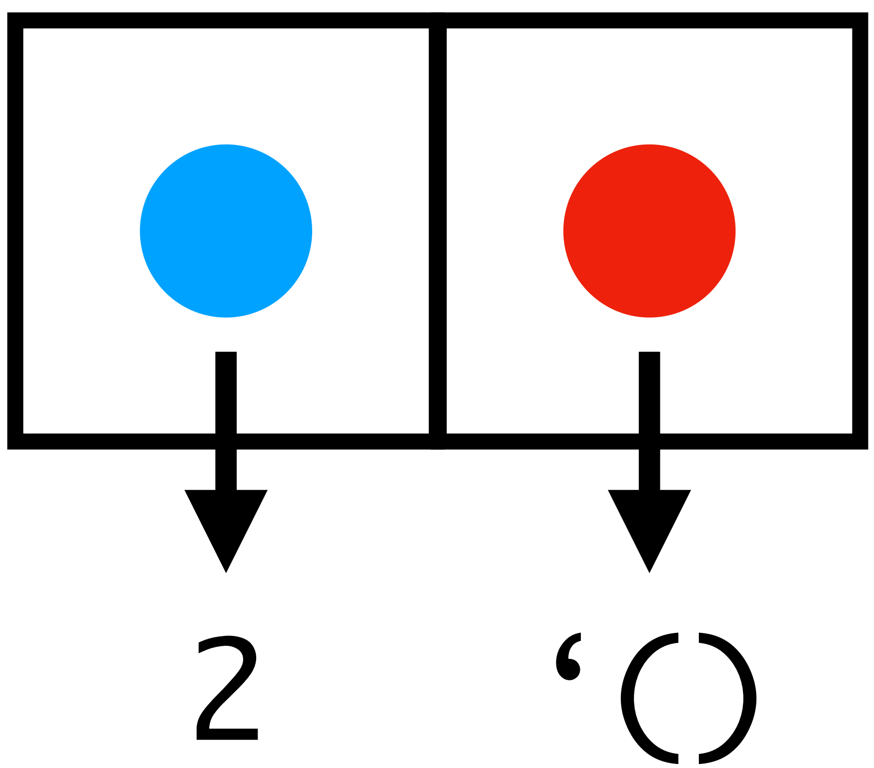
Atoms	`‘sym   23   #\c`
Empty list	`‘()`
cons	`(cons ‘sym 23)`
car/cdr	`(car (cons ‘sym 23))`

Using just this, I can make a list

Using just this, I can make a list

(And everything else in the world, but we'll get back to that…)

If I want to make the list containing 2 I do this (cons 2 ‘())



When I do this, Racket prints it out as a list

‘(2)

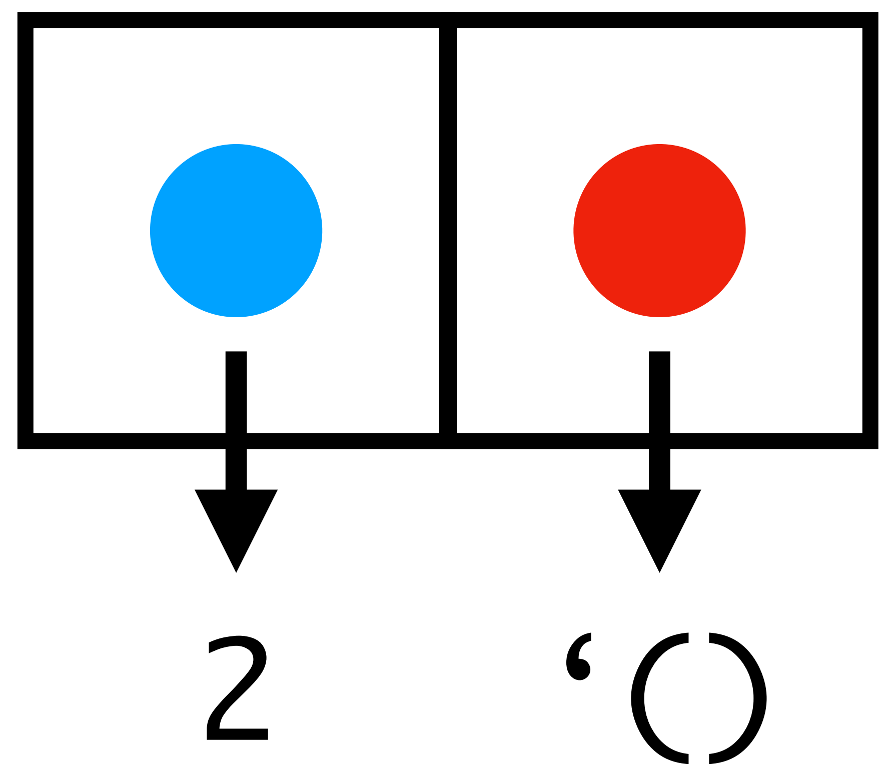
The way to read this is

"The list containing 2, followed by the empty list."

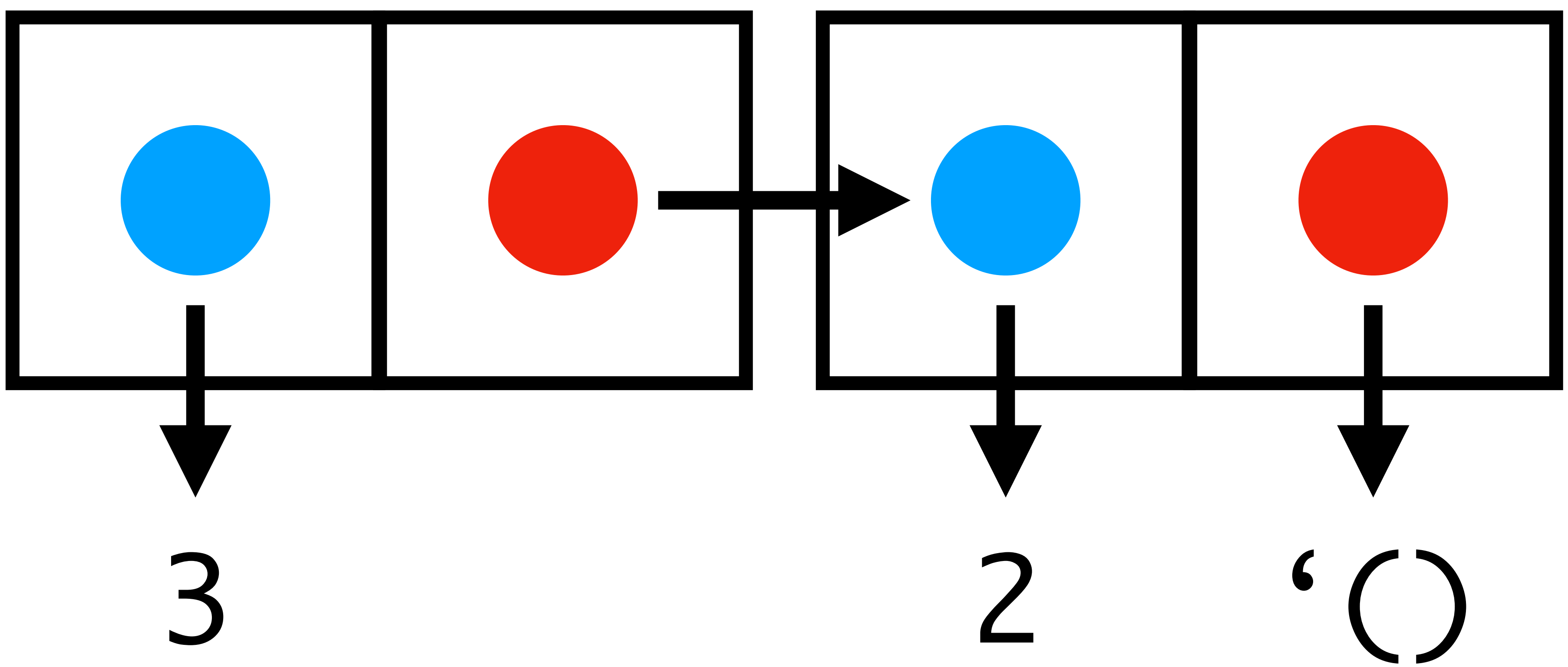
Just as I can build lists of a single element, I can build larger lists from smaller lists…

And I do that by stuffing lists inside other lists…

(cons 2 ‘())



```
(cons 3 (cons 2 ‘()))
```



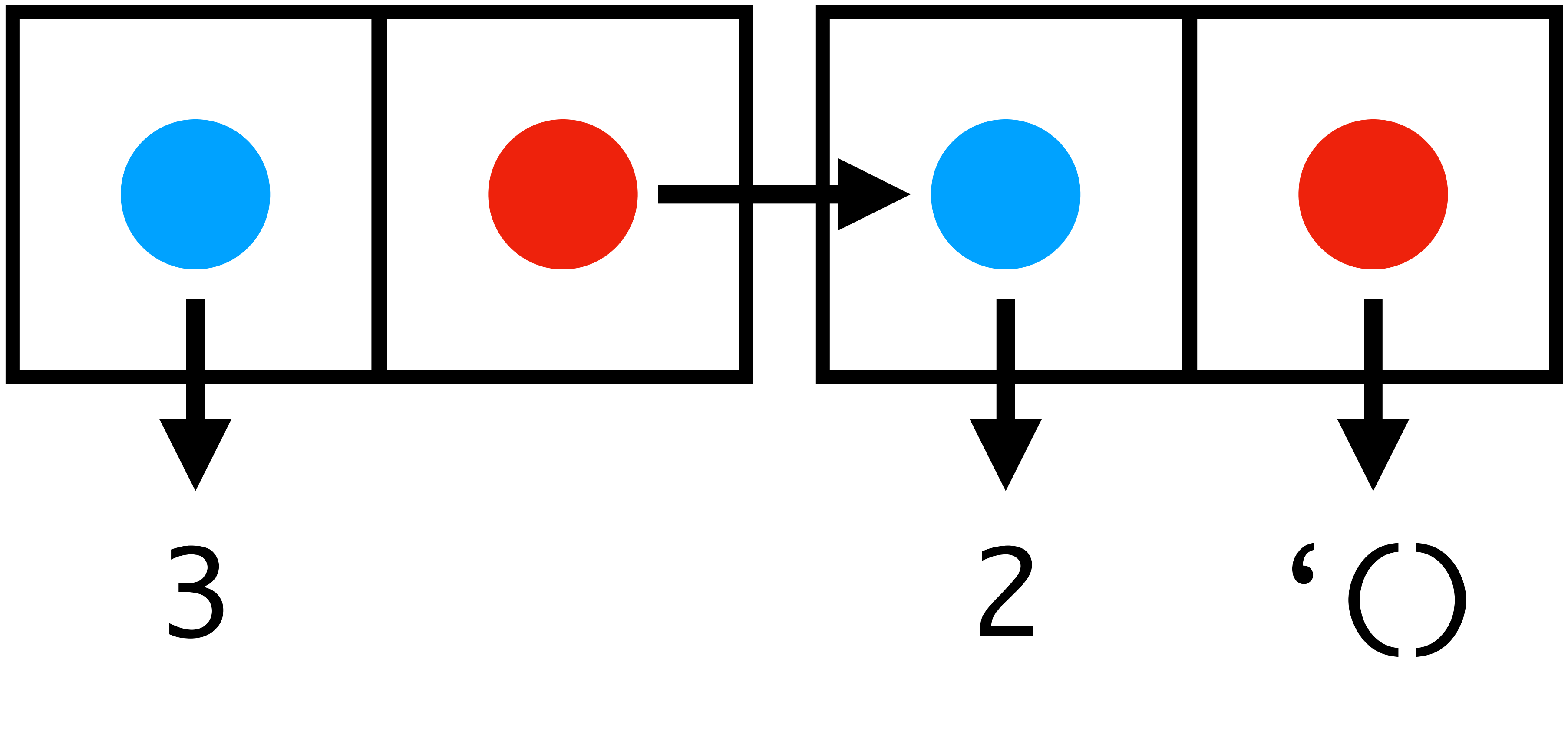
Racket will print this out as

'(3 2)

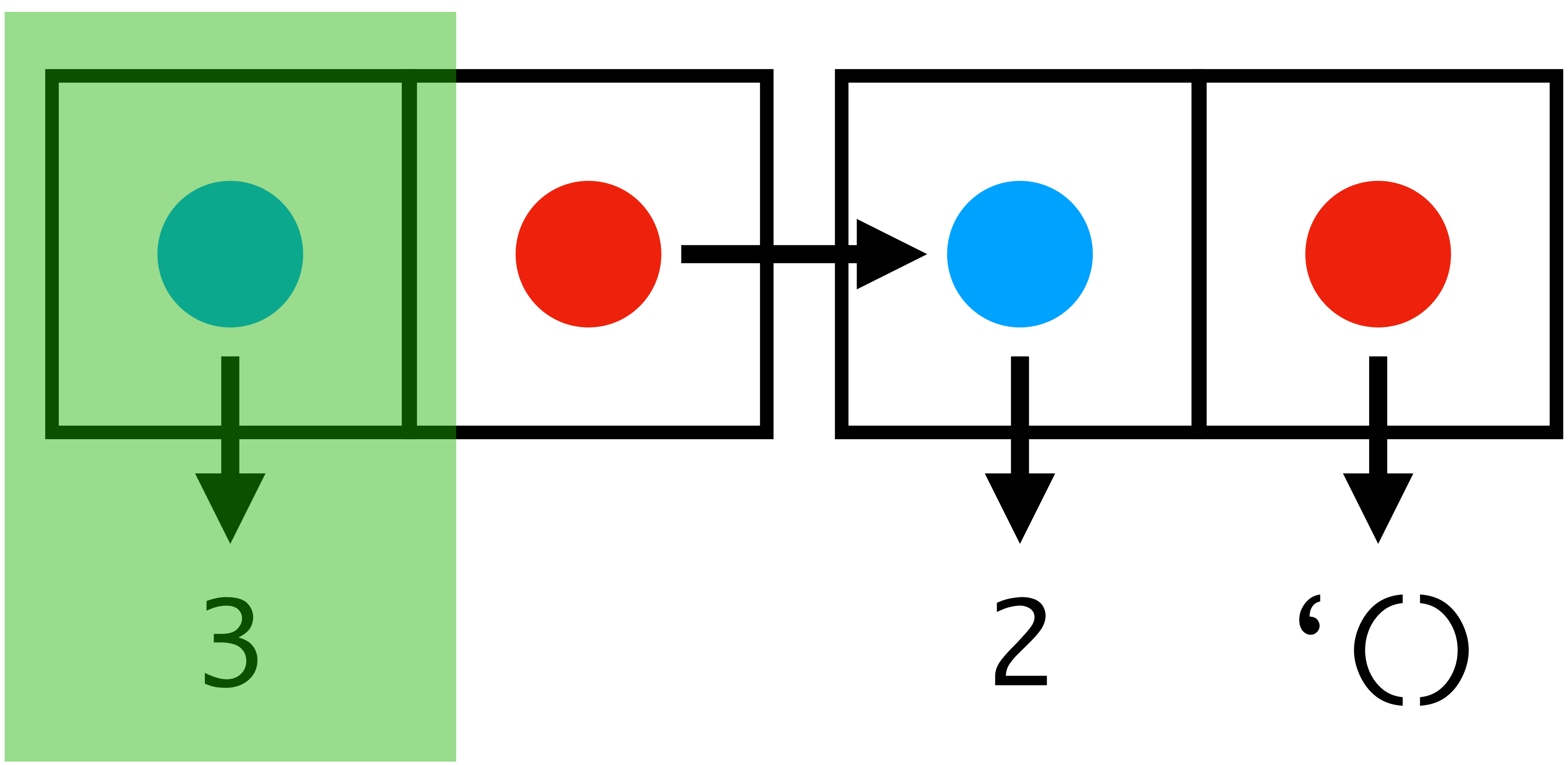
Of course, I probably need at least numbers as primitives right?

To get the head of a list, I use `car`

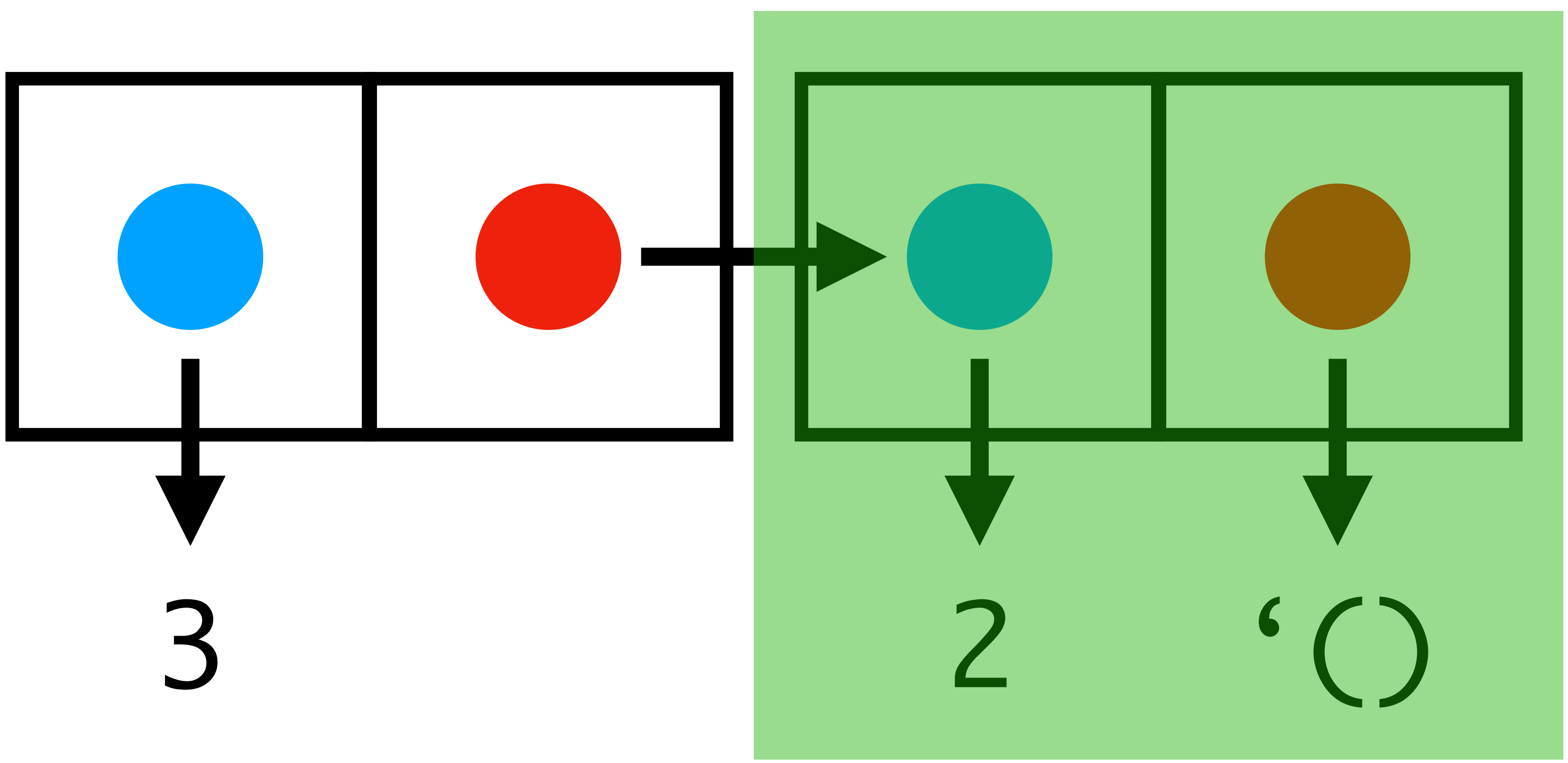
```
(cons 3 (cons 2 ‘()))
```



```
(car
  (cons 3 (cons 2 ‘())))
```

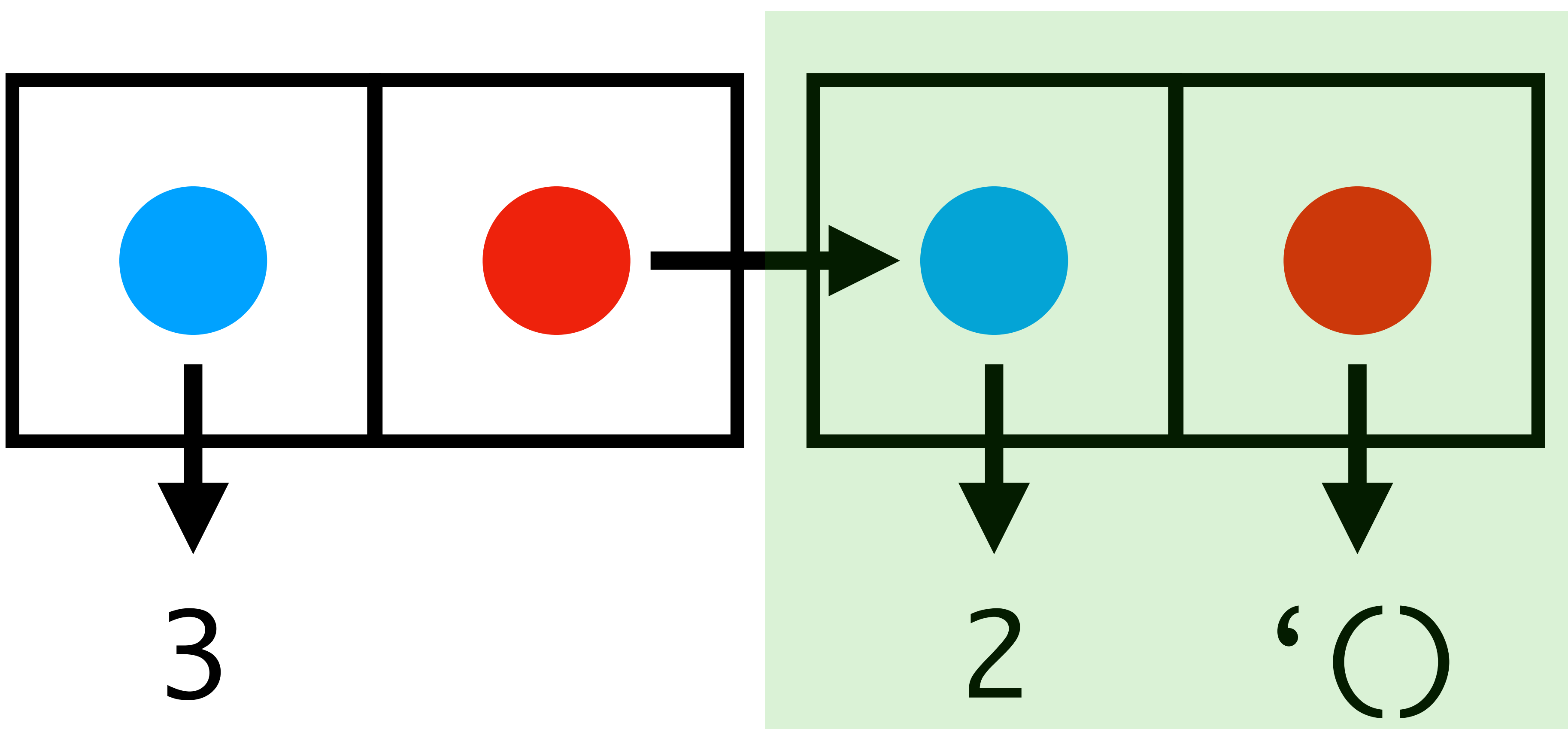


```
(cdr
  (cons 3 (cons 2 ‘())))
```

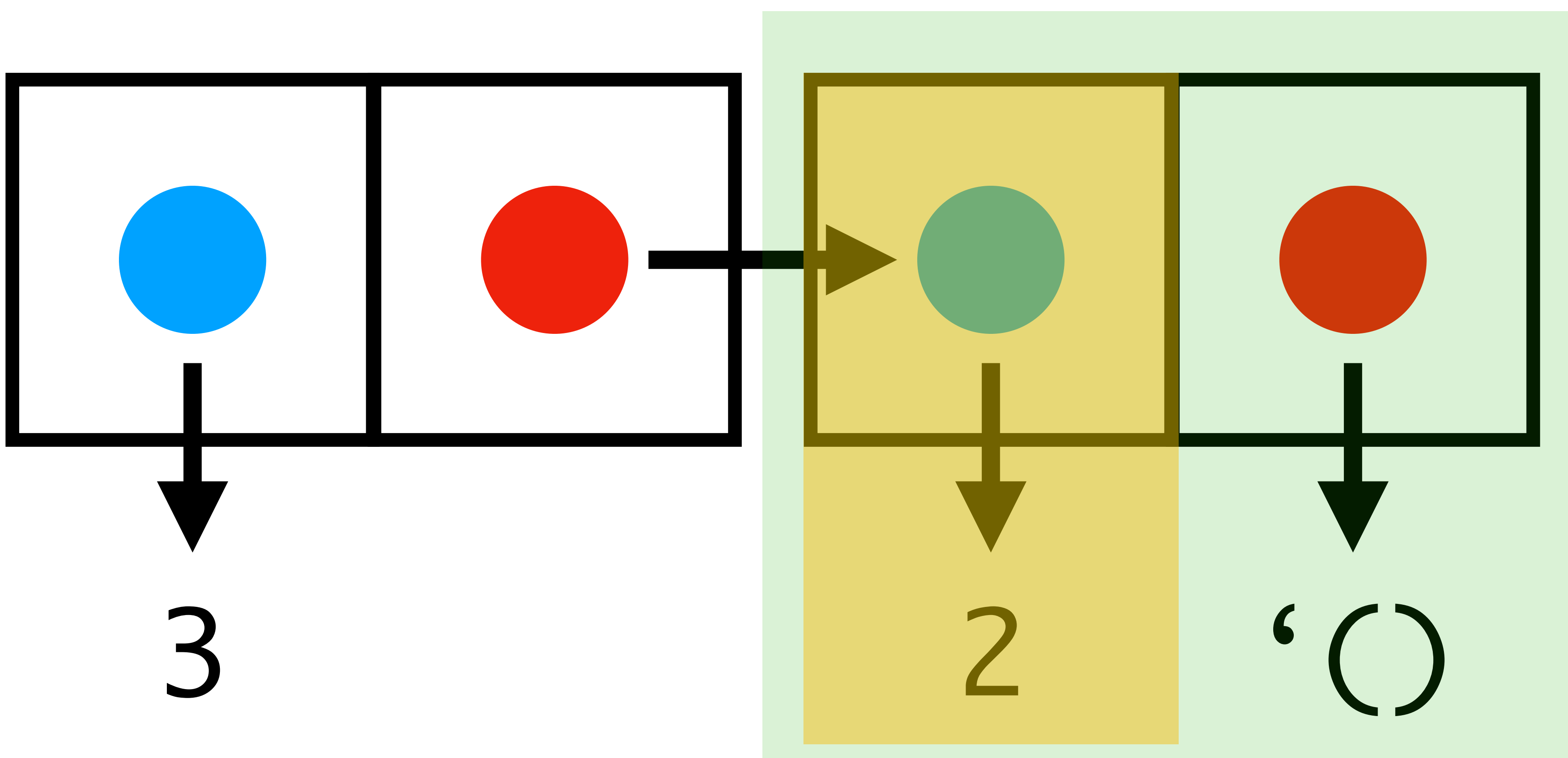


So now how would I get the second element?

```
(cdr
  (cons 3 (cons 2 ‘())))
```



```
(car
 (cdr
   (cons 3 (cons 2 '()))))
```



Racket abbreviates

```
(cons 1 (cons 2 (cons…(cons n ‘())…)))
```

as…

```
‘(1 2 … n)
```

If I wanted to write out lists, I could do so using

```
(cons 1 (cons 2 ...))
```

How do I get the nth element of a list?

```
(define (nth list n)
  (if (= 0 n)
      (car list)
      (nth (cdr list) (- n 1))))
```

Now, write `(map f l)`

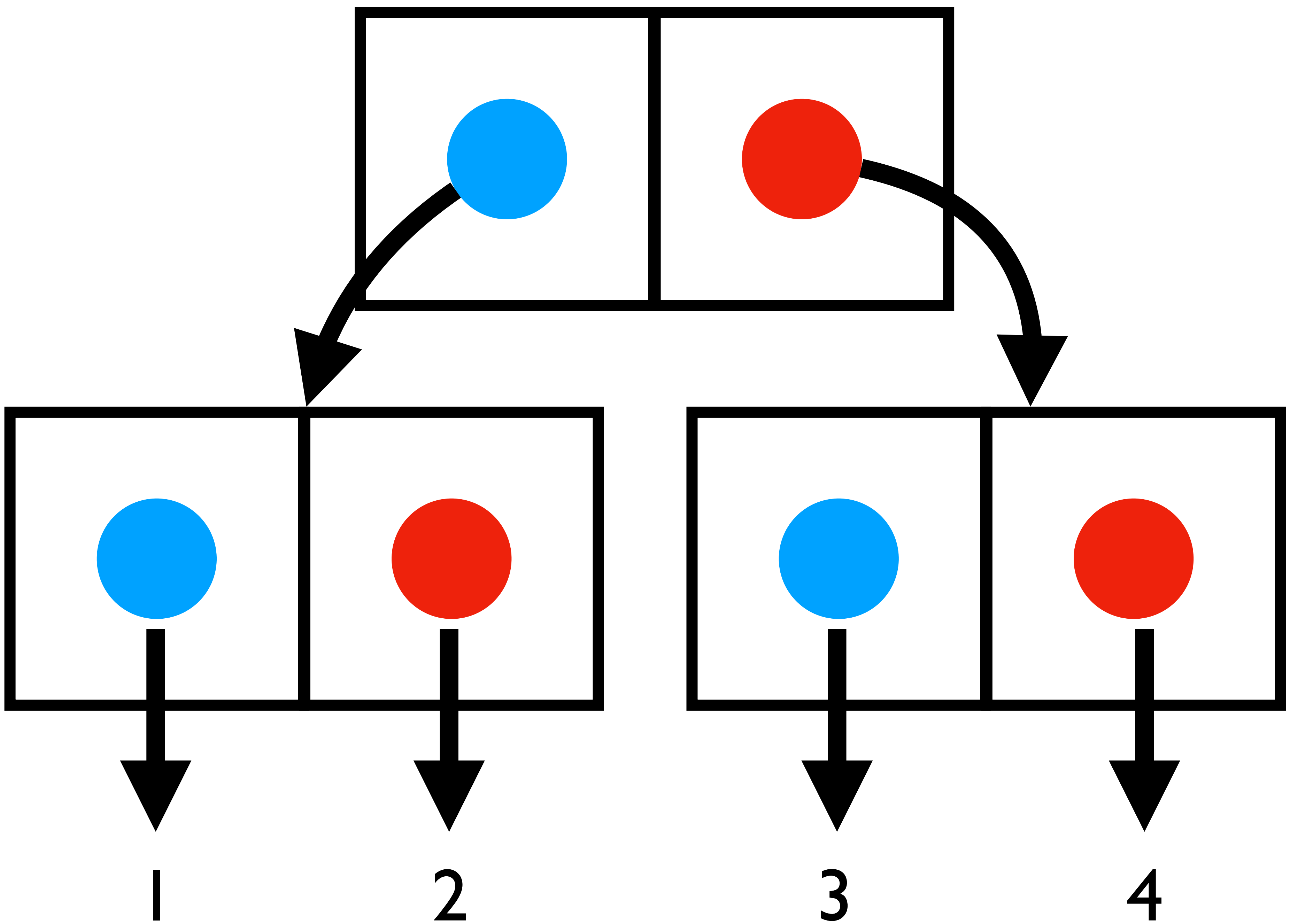
Writing lists would get quite laborious

Instead, I can use the primitive function **list**

```
(list 1 2 ‘serpico)

‘(1 2 serpico)
```

Oh, and actually I can use this to represent trees too


1
2
3
4

How would I build this?

```
(define empty-tree 'empty-tree)

(define (make-leaf num) num)

(define (make-tree left right)
          (cons left right))
```

You define `(left-subtree tree)`

```scheme
(define (least-element tree)
 (if (number? tree)
   tree
   (least-element (left-subtree tree))))
```

But surely I need things like numbers right?

It turns out, you could build those using just

cons, car, cdr, if, =, and ‘()

Define the number n as …

```
'()
'(())
'(() ())
…
```

```
(define (weird-plus i j)
  (if (equal? i '())
      j
      (weird-plus (cdr i)
                  (cons '() j))))
```

```
(weird-plus '(() ()) '(() ())) 
'(() () () ())
```

It turns out, if I'm clever, we can even get rid of
if and **equal**

(Though we shall not do so here..)

I can build my own datatypes in this manner

I usually write **constructor** functions to help me build datatypes

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And I usually write **destructor** functions to access it

```
(define (make-complex real imag)
  (cons real imag))
```

And I usually write **destructor** functions to access it

```scheme
(define (make-complex real imag)
  (cons real imag))

(define (get-real complex)
  (car complex))

(define (get-imag complex)
  (cdr complex))
```

Now, define `(add-complex c1 c2)`

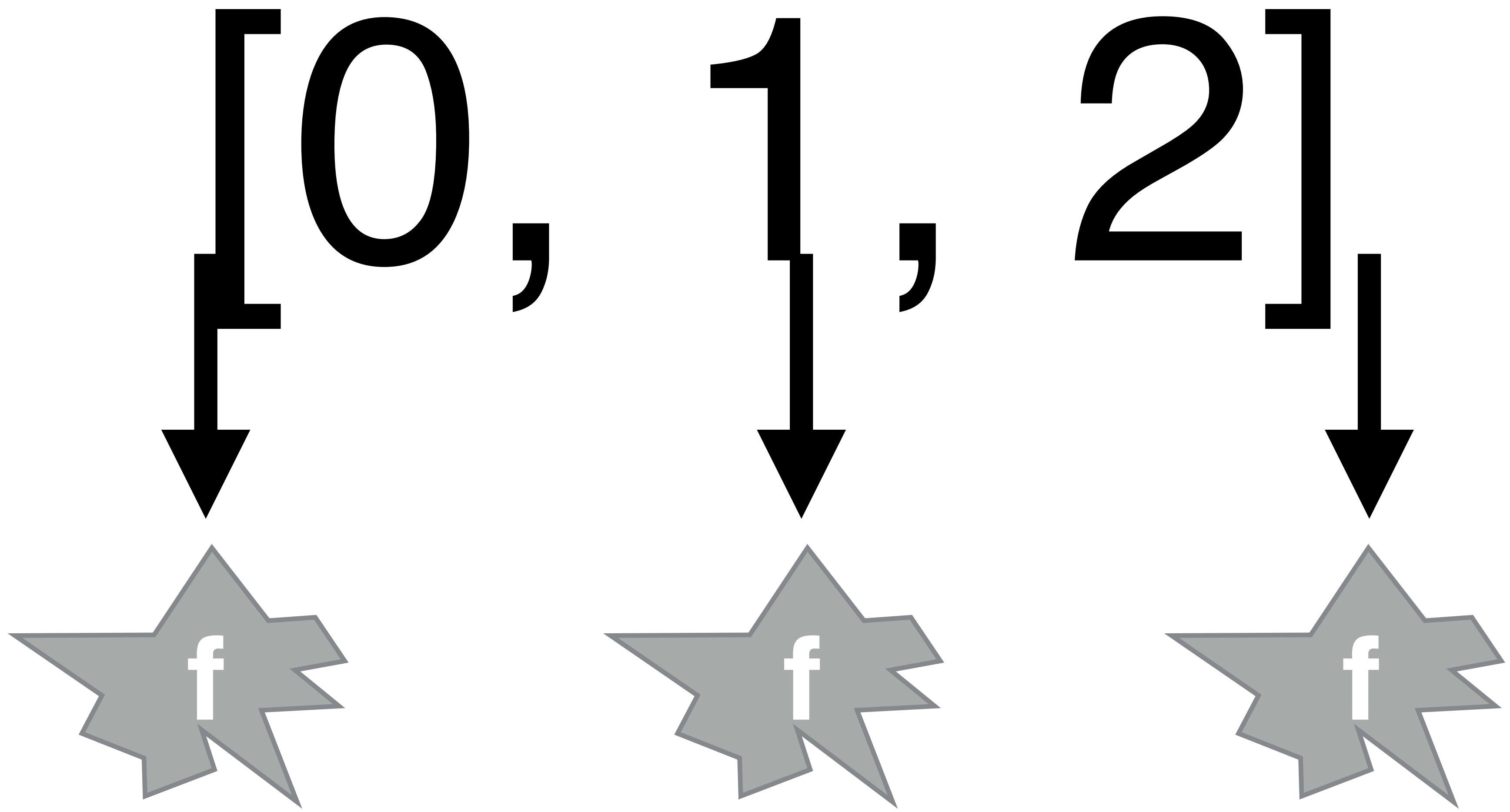
Next, define `(make-cartesian x y)`

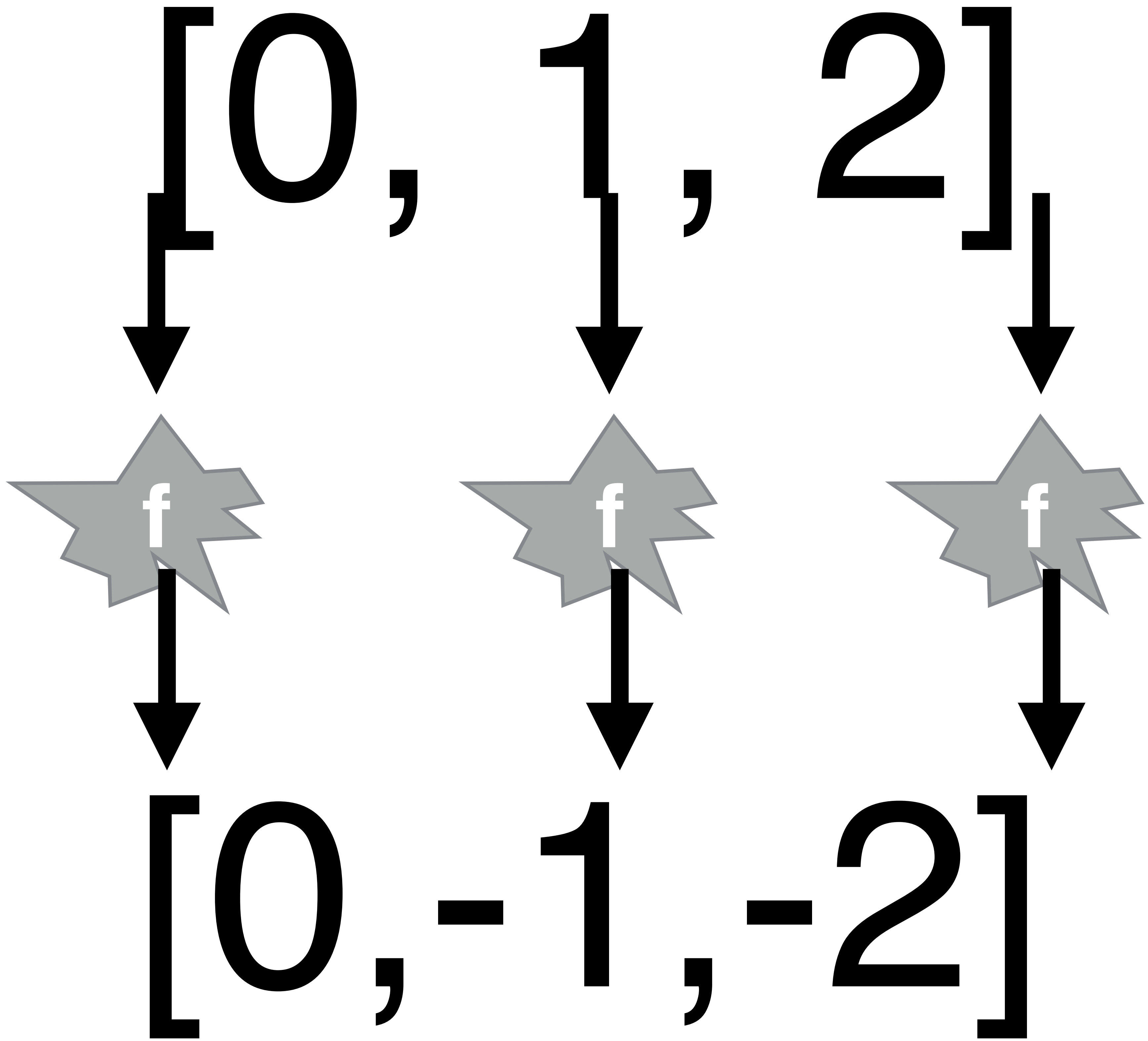
And the associated helper functions

```
> (map (lambda (str) (string-ref str 0)) '("ha" "ha"))
'(#\h #\h)
```

(map f l) takes a function f and applies f to each element of l

[0, 1, 2]


[0, 1, 2]
f
f
f


[0, 1, 2]
f
f
f
[0,-1,-2]

Next class we will talk about…

struct

match

I/O

Intermediate Racket Programming

Tail Recursion

Tail recursion is the way you make recursion fast in functional languages

Anytime I’m going to recurse more then 10k times, I use tail recursion

(I also do it because it’s a fun mental exercise)

Tail Recursion

A function is *tail recursive* if **all** recursive calls are in *tail position*

A call is in tail position if it is the last thing to happen in a function

The following is **not** tail recursive

```
(define (factorial x)
  (if (equal? x 0)
      1
      (* (factorial (- x 1)) x)))
```

The following **is** tail recursive

```
(define (factorial x acc)
  (if (equal? x 0)
      acc
      (factorial (- x 1) (* acc x))))
```

The following is **not** tail recursive

```
(define (factorial x)
   (if (equal? x 0)
       1
       (* (factorial (- x 1)) x)))
```

Explain to the person next to you why this is

The following **is** tail recursive

```
(define (factorial x acc)
  (if (equal? x 0)
      acc
      (factorial (- x 1) (* acc x))))
```

Swap. Explain to the person next to you why this is

This isn’t merely trivia!

```
(define (factorial x acc)
    (if (equal? x 0)
        acc
        (factorial (- x 1) (* acc x))))
; .. Later
(factorial 2 1)
```

```
(define (factorial x acc)
    (if (equal? x 0)
        acc
        (factorial (- x 1) (* acc x))))
; .. Later
(factorial 2 1)
```

>factorial 2 1

factorial 2 1

```
(define (factorial x acc)
    (if (equal? x 0)
        acc
        (factorial (- x 1) (* acc x))))
; .. Later
(factorial 2 1)
```

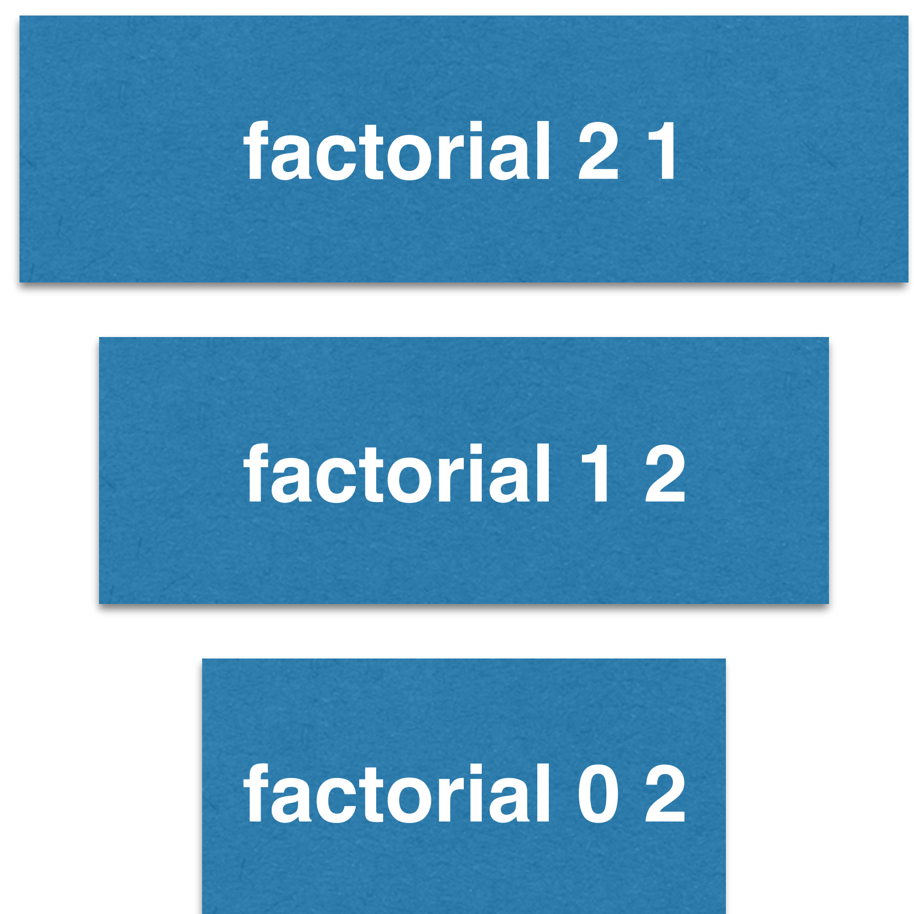
```
>factorial 2 1
    >factorial 1 2
```

factorial 2 1

factorial 1 2

```
(define (factorial x acc)
    (if (equal? x 0)
        acc
        (factorial (- x 1) (* acc x))))
; .. Later
(factorial 2 1)
```

```
>factorial 2 1
    >factorial 1 2
        >factorial 0 2
```



```
(define (factorial x acc)
    (if (equal? x 0)
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; .. Later
(factorial 2 1)
```
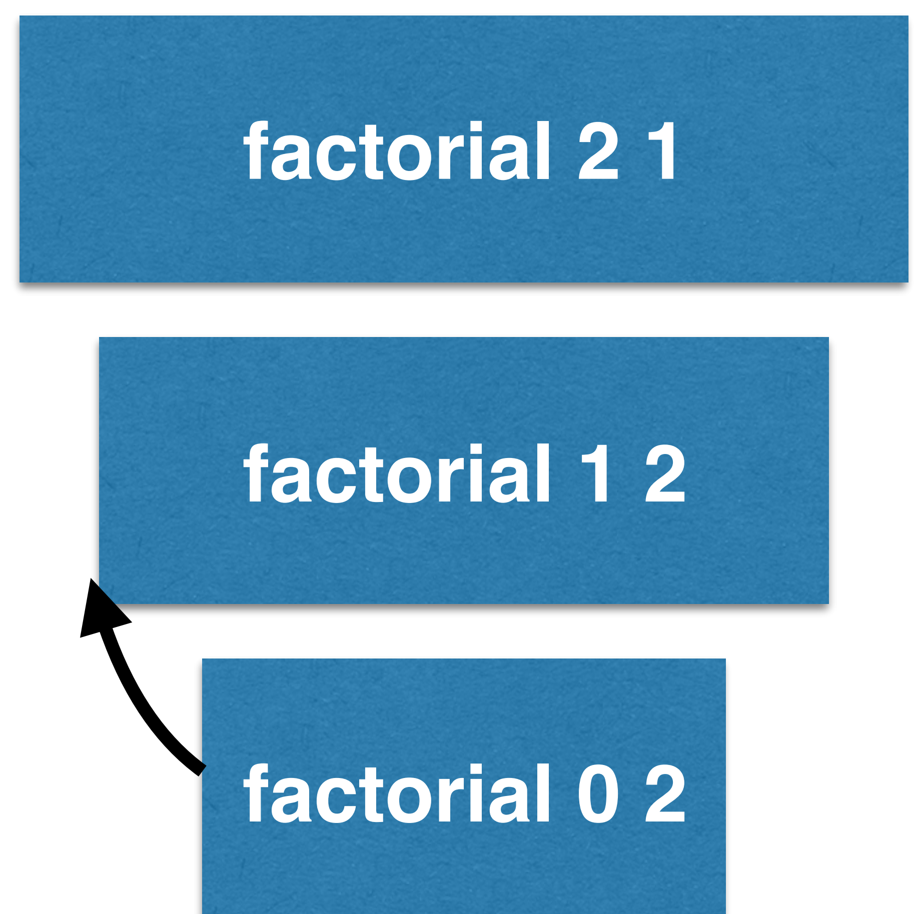
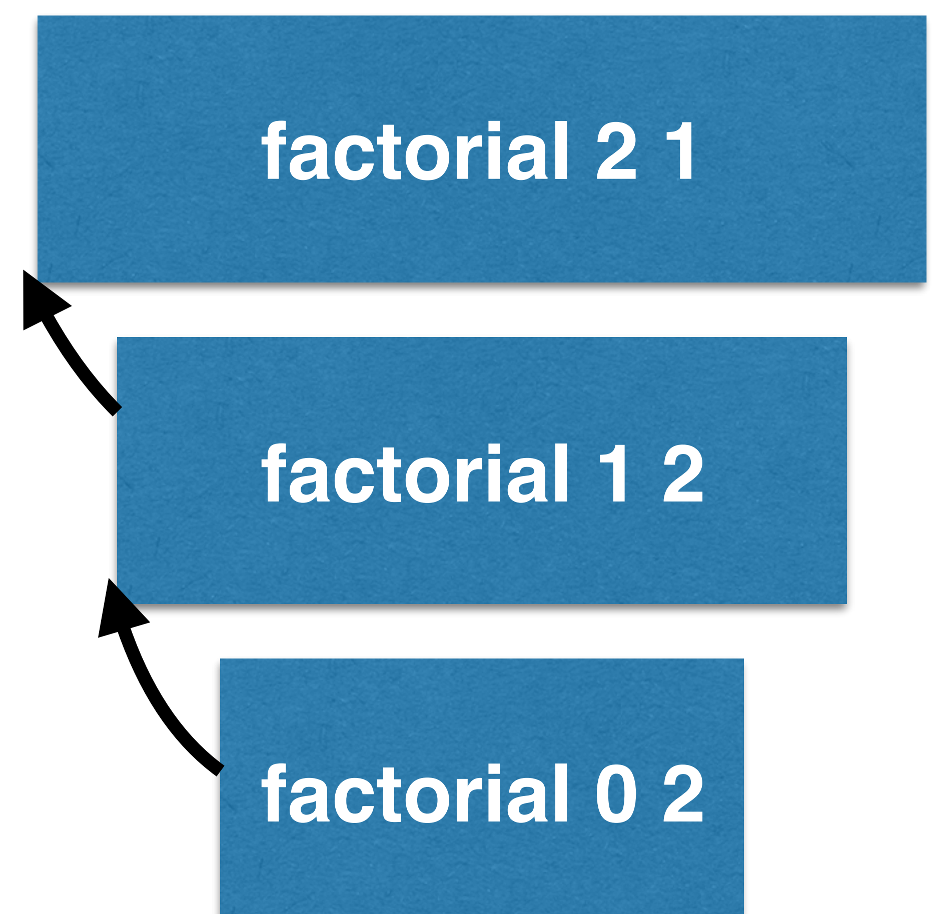

```
>factorial 2 1

    >factorial 1 2

        >factorial 0 2
```



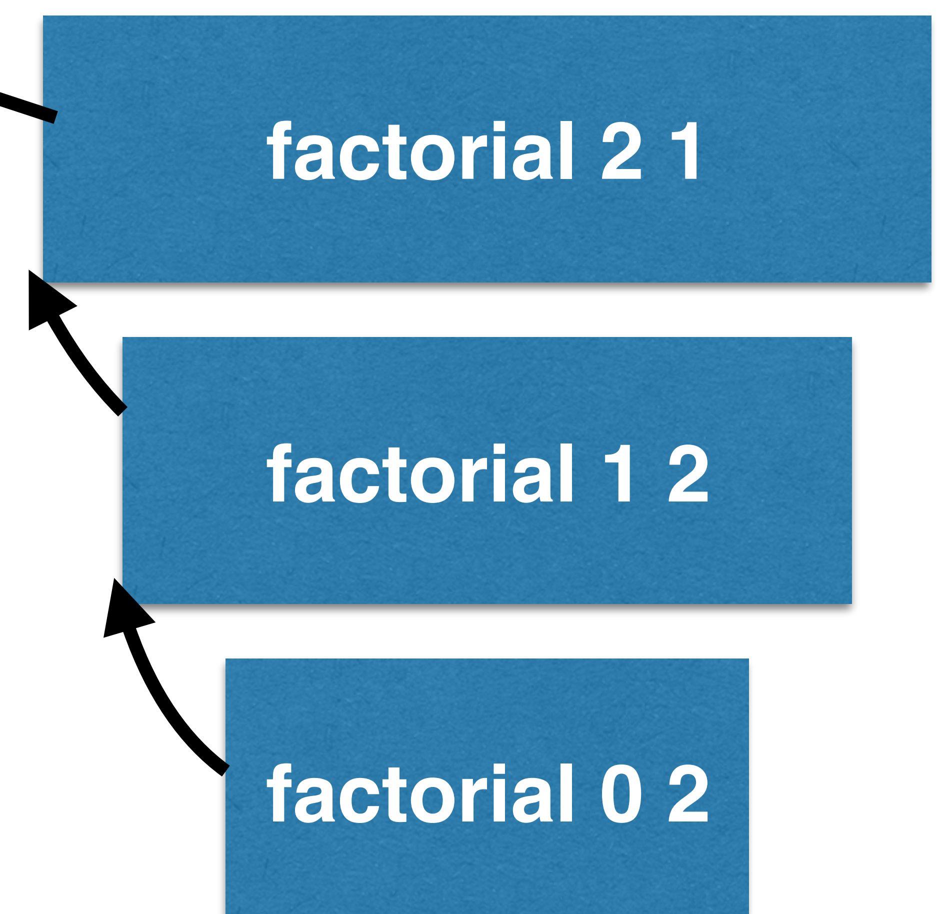
```
(define (factorial x acc)
   (if (equal? x 0)
       acc
       (factorial (- x 1) (* acc x))))
; .. Later
(factorial 2 1)
```

```
>factorial 2 1
    >factorial 1 2
        >factorial 0 2
```



```
(define (factorial x acc)
   (if (equal? x 0)
       acc
       (factorial (- x 1) (* acc x))))
; .. Later
(factorial 2 1)
```

```
>factorial 2 1
    >factorial 1 2
        >factorial 0 2
```



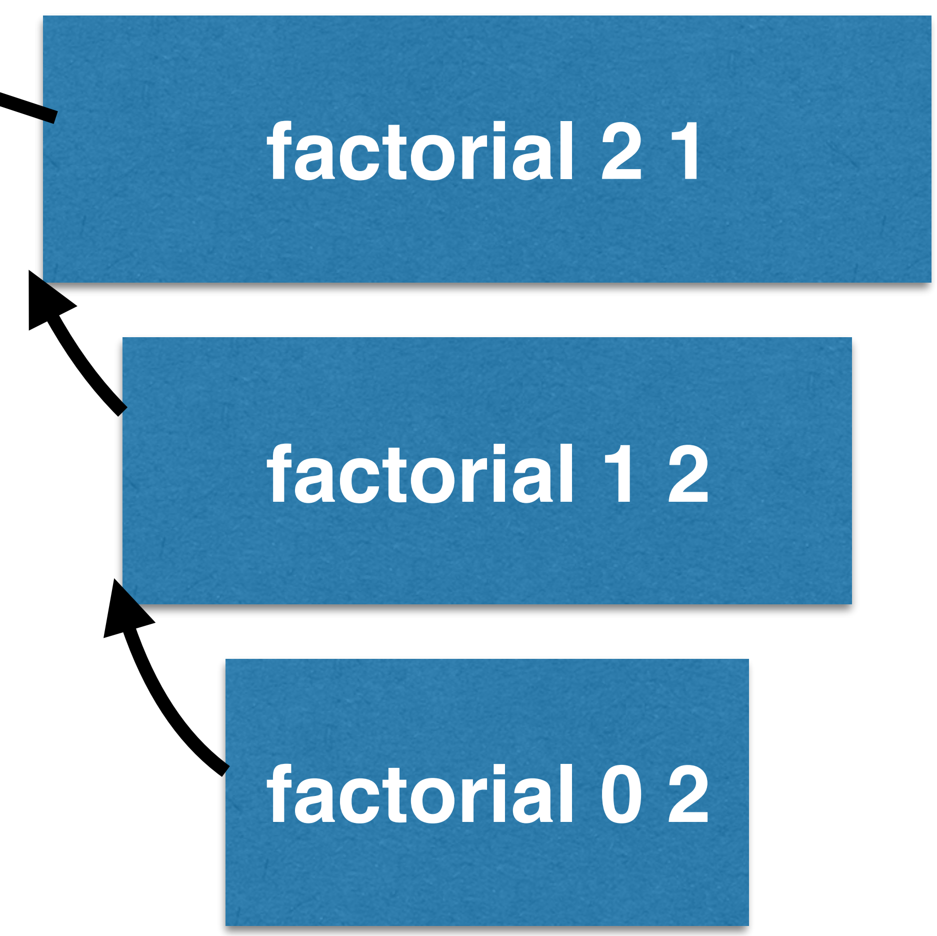
```
(define (factorial x acc)
    (if (equal? x 0)
        acc
        (factorial (- x 1) (* acc x))))
; .. Later
(factorial 2 1)
```

But wait!
I don’t need the stack at all!

>factorial 2 1

>factorial 1 2

>factorial 0 2



Insight: in tail recursion, the stack is just used for copying back the results

So just forget the stack. Just give the final result to the original caller.

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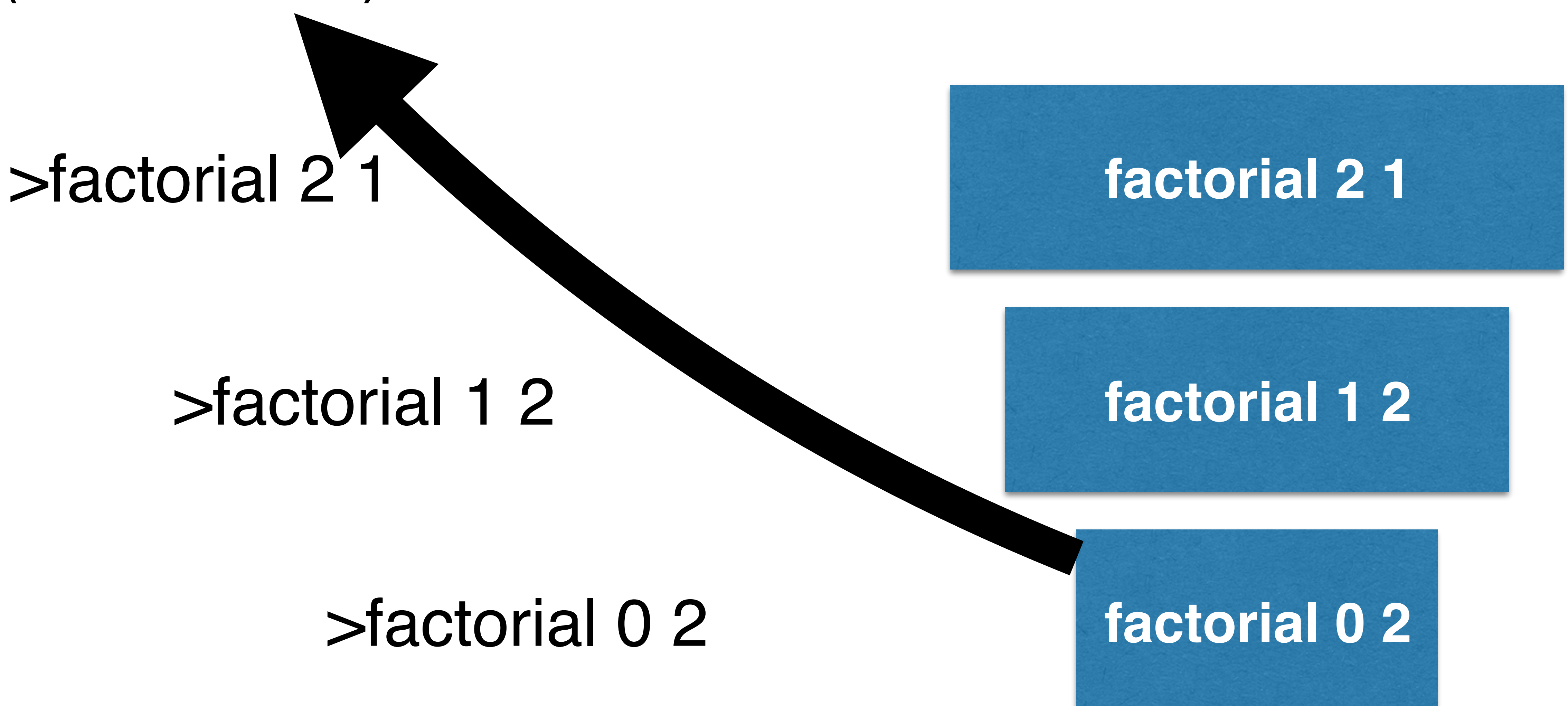
So just forget the stack. Just give the final result to the original caller.

Insight: in tail recursion, the stack is just used for copying back the results

This is called “tail call optimization”

```
(define (factorial x acc)
    (if (equal? x 0)
        acc
        (factorial (- x 1) (* acc x))))
; .. Later
(factorial 2 1)
```



Why **couldn't** I do that with this?

```
(define (factorial x)
    (if (equal? x 0)
        1
        (* (factorial (- x 1)) x)))
```

Talk it out with neighbor

Tail recursion for λ and profit…

To make a function tail recursive…

- add an extra accumulator argument
- that tracks the result you're building up
- then return the result
- might have to use more than one extra arg
- Call function with base case as initial accumulator

This isn't the only way to do it, just a nice trick
that usually results in clean code…

```
(define (factorial x)
  (if (equal? x 0)
    1
    (* (factorial (- x 1)) x)))
```

```
(define (factorial-tail x acc)
  (if (equal? x 0)
    acc
    (factorial-tail (- x 1) (* acc x))))
(define (factorial x) (factorial-tail x 1))
```

```
(define (max-of-list l)
  (cond [(eq? (length l) 1) 1]
        [(empty? l) (raise 'empty-list)]
        [else (max (first l) (max-of-list (rest l))
)]))
```

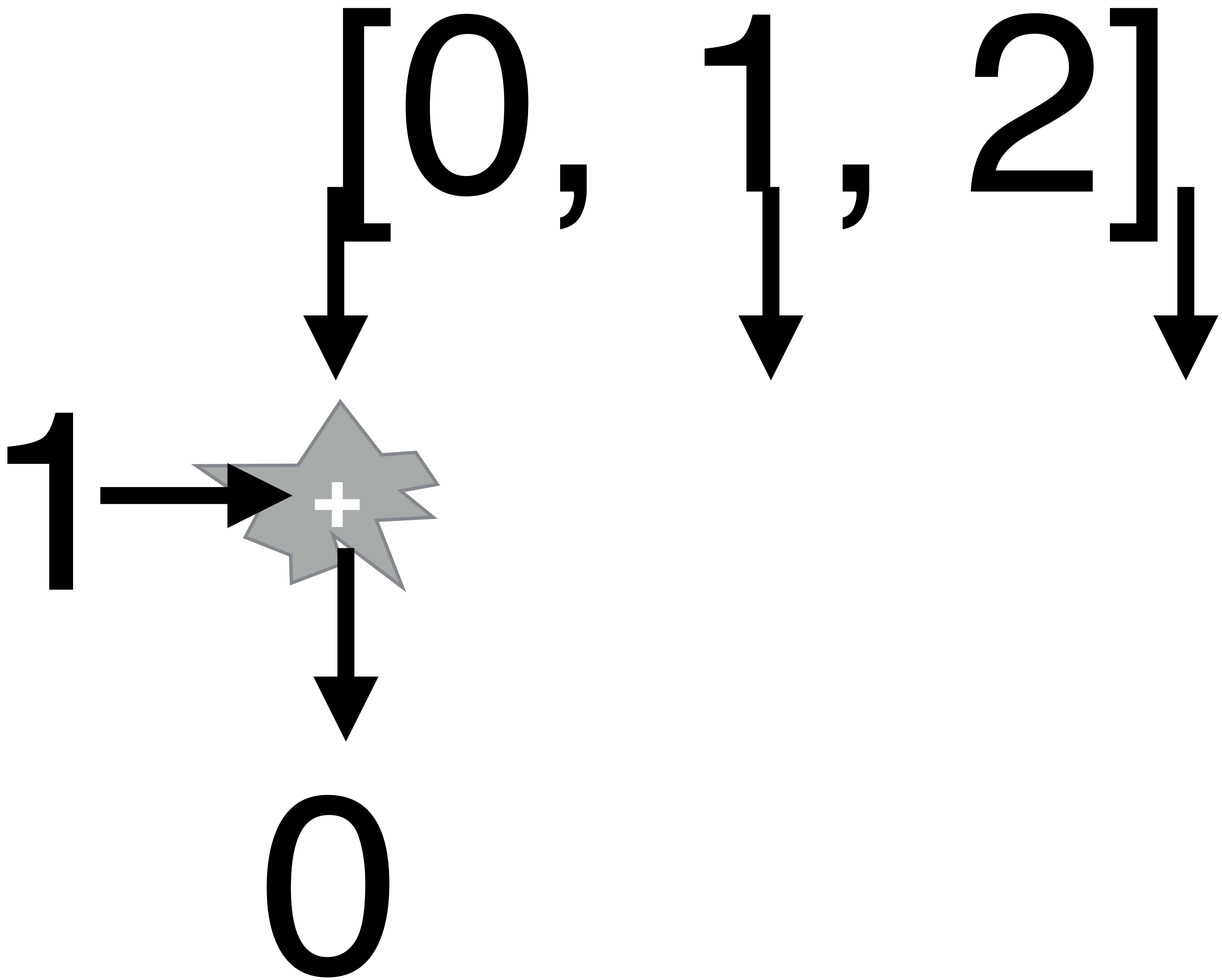
Write this as a tail-recursive function

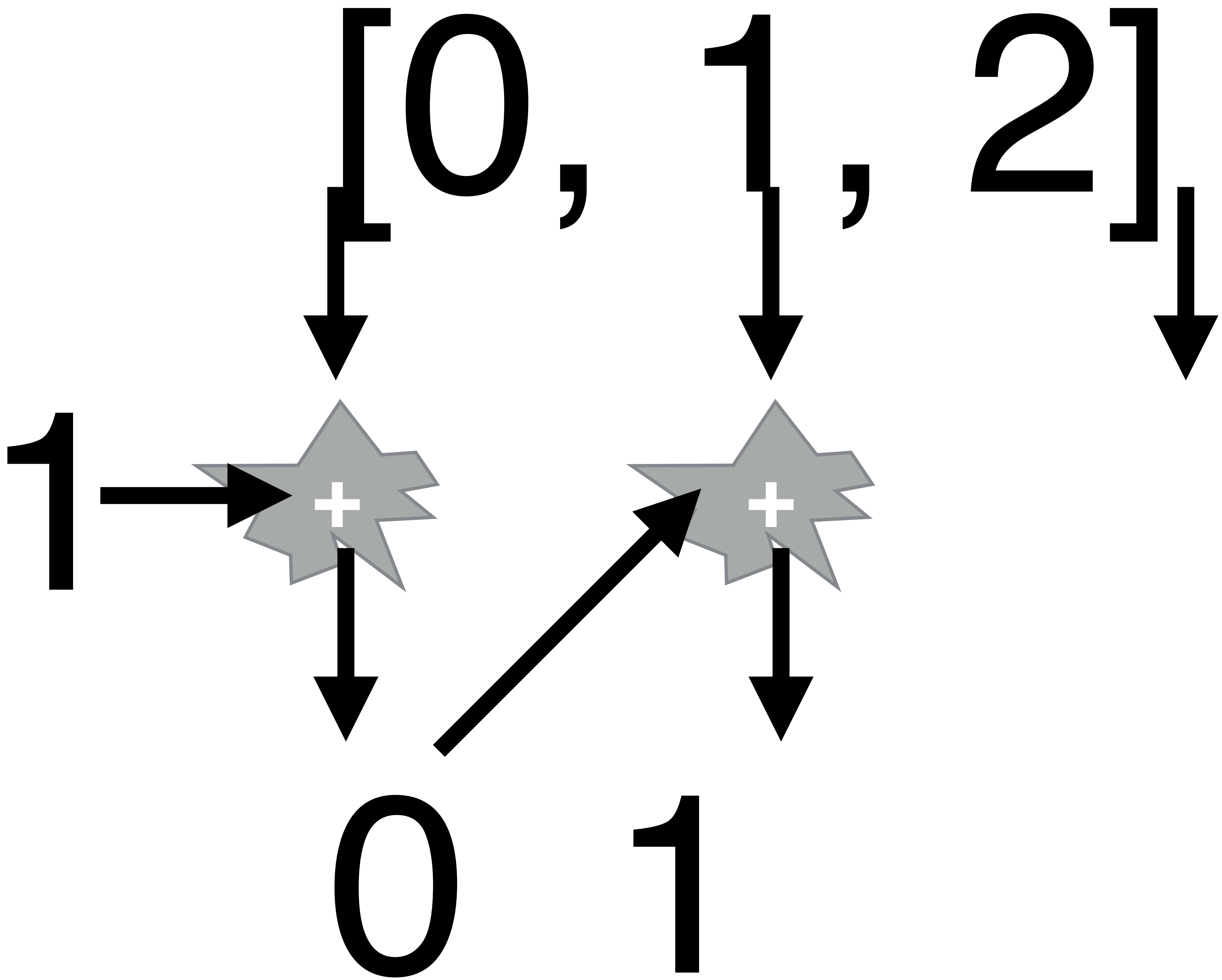
foldl

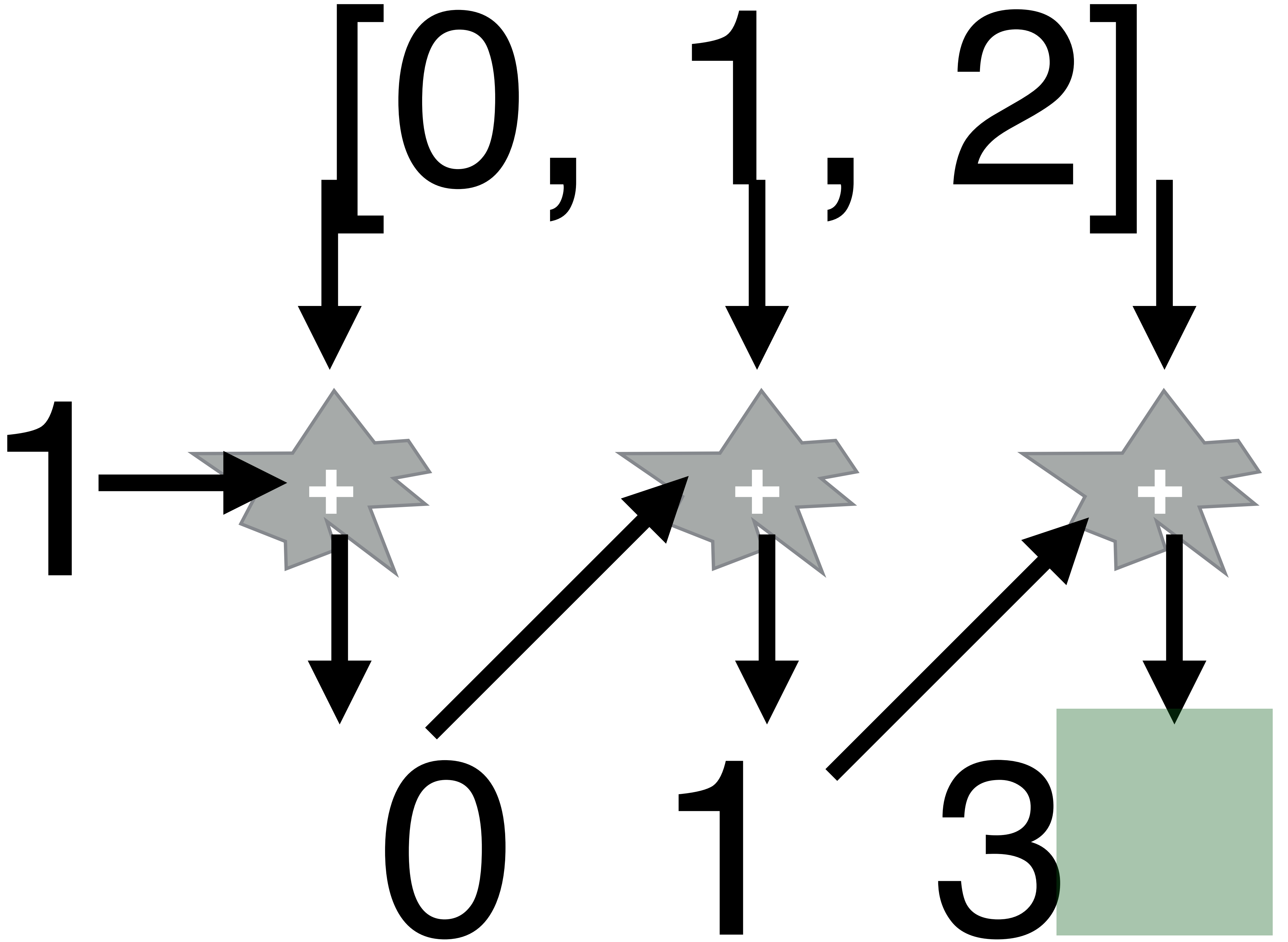
Like map, a higher order function operating on lists

(foldl / 1 ‘(1 2 3)) = (/ 3 (/ 2 (/ 1 1)))

(foldl + 0 ‘(1 2 3)) = (+ 3 (+ 2 (+ 1 0)))


[0, 1, 2]
1
+
0


[0, 1, 2]
1
+
+
0
1


[0, 1, 2]
1
0 1 3

```
(define (concat-strings l)
  (foldl (lambda (next_element accumulator)
       (string-append next_element accumulator))
       ""
       (reverse l)))
```

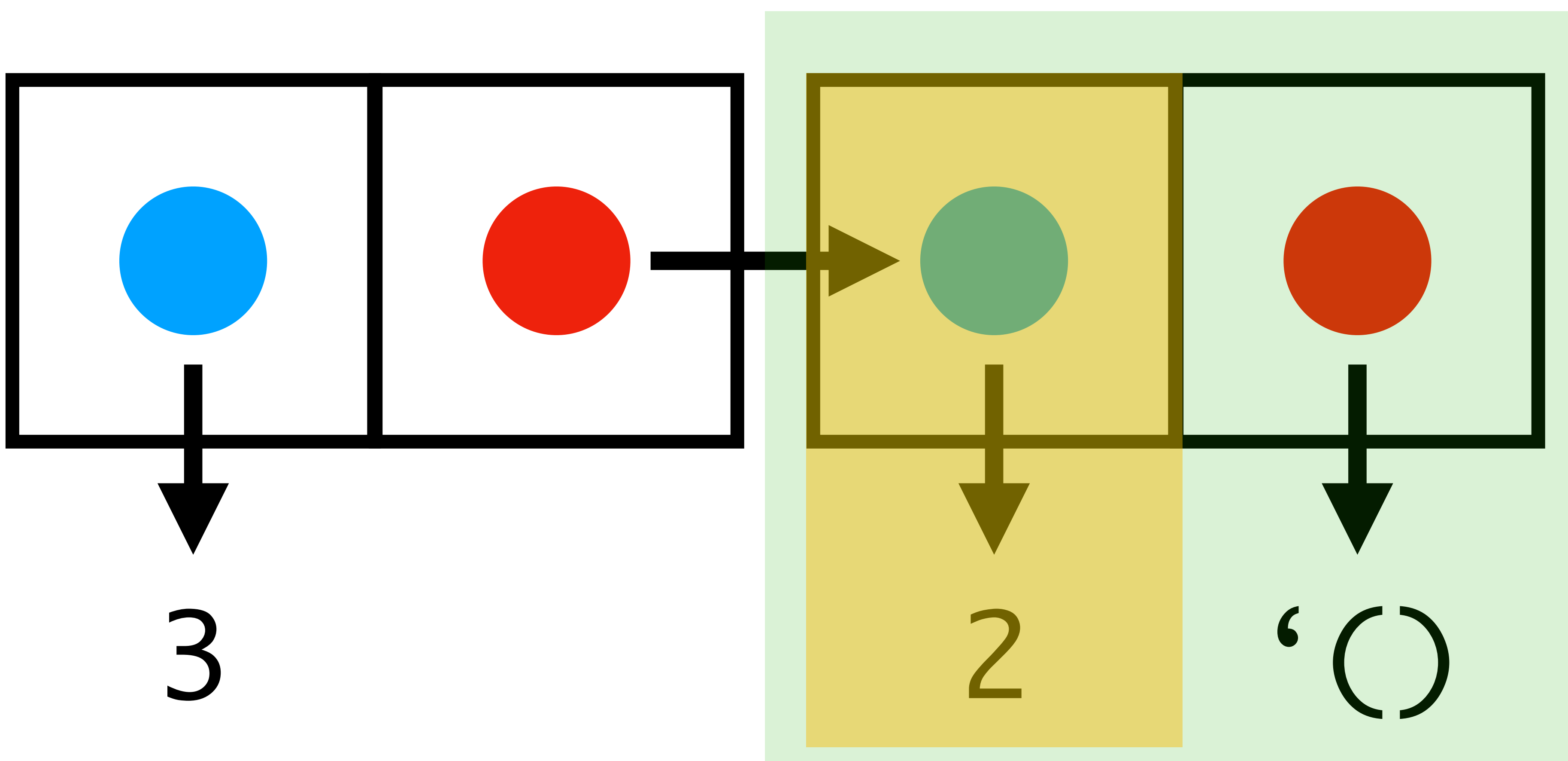
Challenge: use foldl to define max-of-list

**Challenge: define foldl

Structures, Pattern Matching, and Contracts

Last time

```
(car
 (cdr
  (cons 3 (cons 2 ‘()))))
```



This time

5 Programmer-Defined Datatypes

New datatypes are normally created with the `struct` form, which is the topic of this chapter. The class-based object system, which we defer to Classes and Objects, offers an alternate mechanism for creating new datatypes, but even classes and objects are implemented in terms of structure types.

5.1 Simple Structure Types: `struct`

To a first approximation, the syntax of `struct` is

```
(struct struct-id (field-id ...))
```

Examples:

```
(struct posn (x y))
```

The `struct` form binds *`struct-id`* and a number of identifiers that are built from *`struct-id`* and the *`field-id`*s:

- *`struct-id`* : a *constructor* function that takes as many arguments as the number of *`field-id`*s, and returns an instance of the structure type.

  Example:

  ```
  > (posn 1 2)
  #<posn>
  ```

- *`struct-id`*? : a *predicate* function that takes a single argument and returns `#t` if it is an instance of the structure type, `#f` otherwise.

  Examples:

Use **struct** to define a new datatype

```
(struct empty-tree ())

(struct leaf (elem))

(struct tree (left right))
```

Copy these

```
(struct empty-tree ())

(struct leaf (elem))

(struct tree (value left right))
```

```
(empty-tree)

(leaf 23)

(tree 12 (empty-tree) (leaf 23))
```

Racket automatically generates helpers…

```
tree?

tree-left

tree-right
```

Write `max-of-tree`

Use the helpers

Pattern matching

Pattern matching allows me to tell Racket the "shape" of what I'm looking for

Manually pulling apart data structures is laborious

```
(define (max-of-tree t)
  (match t
    [(leaf e) e]
    [(tree v _ (empty-tree)) v]
    [(tree _ _ r) (max-of-tree r)]))
```

Variables are bound in the match, refer to in body

```
(define (max-of-tree t)
  (match t
    [(leaf e) e]
    [(tree v _ (empty-tree)) v]
    [(tree _ _ r) (max-of-tree r)]))
```

Note: match struct w/ (name params…)

```
(define (max-of-tree t)
  (match t
    [(leaf e) e]
    [(tree v _ (empty-tree)) v]
    [(tree _ _ r) (max-of-tree r)]))
```

Define `is-sorted`

Can match a list of x’s

```
(list x y z …)

(1 2 3 4)

x = 1 y = 2 z = ‘(3 4)
```

Can match cons cells too…

```
(cons x y)
```

Variants include things like match-let

10

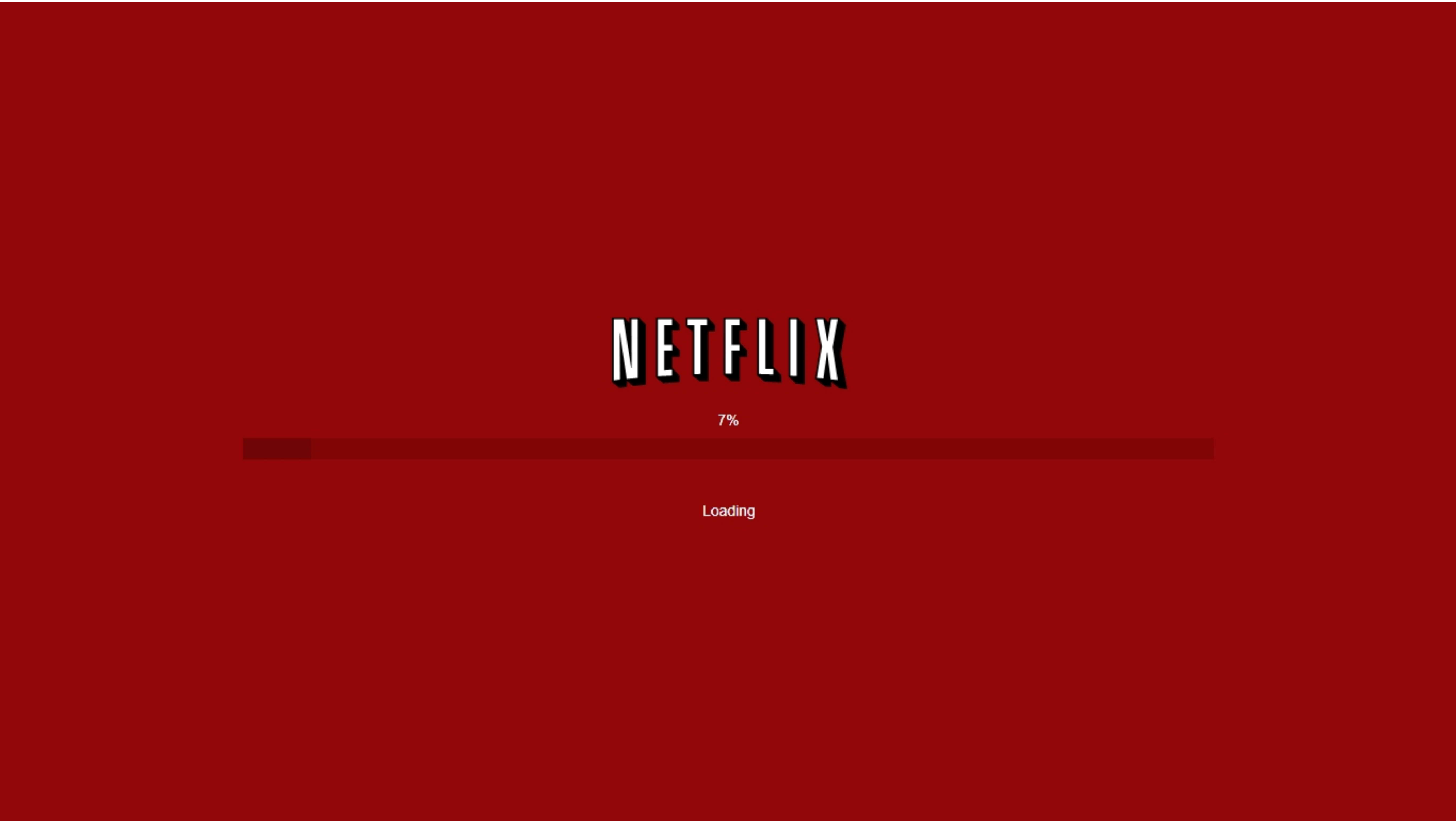
Racket has a “reader”

(read)

Racket “reads” the input one *datum* at a time

```
> (read)
(1 2 3)
'(1 2 3)
> (read)
1 2 3
1
> (read)
2
> (read)
3
>
```

Read will “buffer” its input


NETFLIX
7%
Loading

```
(read-line)
```

```
(open-input-file)
```

Contracts

```
(define (reverse-string s)
  (list->string (reverse (string->list s))))
```

Write out the call and return type of this for yourself

```
(define (factorial i)
  (cond
    [(= i 1) 1]
    [else (* (factorial (- i 1)) i)]))
```

What are the call / return types?

What is the pre / post condition?

```
(define (gt0? x) (> x 0))
```

```
(define/contract (factorial i)
  (-> gt0? gt0?)
  (cond
    [(= i 1) 1]
    [else (* (factorial (- i 1)) i)]))
```

Now in tail form…

```
(define (fac-tail i)
  (letrec ([h (lambda (i acc)
                (cond
                  [(= i 0) acc]
                  [else (h (- i 1) (* acc i))]))])
    (h i 1)))
```

Now, let's say I want to say it's equal to factorial…

```
(define/contract (fac-tail i)
  (->i ([x (>=/c 0)])
       [result (x) (lambda (result) (= (factorial x) result))])
  (letrec ([h (lambda (i acc)
                (cond
                  [(= i 0) acc]
                  [else (h (- i 1) (* acc i))]))])
    (h i 1)))
```

```
(->i ([x (>=/c 0)])
     [result (x) (lambda (result) (= (factorial x) result))])
```

```
(define/contract (reverse-string s)
  (-> string? string?)
  (list->string (reverse (string->list s))))
```

```
(define/contract (reverse-string s)
  (-> string? string?)
  (list->string (reverse (string->list s))))
```

```
(<=/c 2)
```

`<=/c` takes an argument `x`, returns a function f that takes an argument `y`, and `f(y) = #t` if `x <= y`

`<=/c` takes an argument `x`, returns a function f that takes an argument `y`, and `f(y) = #t` if `x <= y`

(Note: <=/c is also doing some bookeeping, but we won't worry about that now.)

Challenge: write <=/c

Three stories

```
(define/contract (call-and-concat f s1 s2)
  (-> (-> string? string?) string? string? string?)
  (string-append (f s1) (f s2)))
```

```
(define (reverse-string s)
  (list->string (reverse (string->list s))))
```

Scenario: you call call-and-concat with reverse

Scenario: you call call-and-concat with reverse, 12, and “12"

Now define

```
(define/contract (call-and-concat f s1 s2)
  (-> (-> string? string?) string? string? string?)
  (length (string-append (f s1) (f s2))))
```

Now define

```
(define/contract (call-and-concat f s1 s2)
  (-> (-> string? string?) string? string? string?)
  (length (string-append (f s1) (f s2))))
```

What went wrong?

Now define

```
(define/contract (call-and-concat f s1 s2)
  (-> (-> string? string?) string? string? string?)
  (length (string-append (f s1) (f s2))))
```

What went wrong?

Who is to blame?